1997

A spatial econometric model for transboundary air pollution control treaties: an analysis of noncooperative international behavior

Keith Allen Sargent
Iowa State University

Recommended Citation
Sargent, Keith Allen, "A spatial econometric model for transboundary air pollution control treaties: an analysis of noncooperative international behavior " (1997). *Retrospective Theses and Dissertations*. 11741.
https://lib.dr.iastate.edu/rtd/11741

INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.

UMI

A Bell & Howell Information Company
300 North Zeeb Road, Ann Arbor MI 48106-1346 USA
313/761-4700 800/521-0600

A spatial econometric model for transboundary air pollution control treaties:

An analysis of noncooperative international behavior

by

Keith Allen Sargent

A dissertation submitted to the graduate faculty

in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Economics

Major Professor: Todd Sandler

Iowa State University

Ames, Iowa

1997

UMI Number: 9725454

UMI
300 North Zeeb Road
Ann Arbor, MI 48103

Graduate College
Iowa State University

This is to certify that the Doctoral dissertation of

Keith Allen Sargent

has met the thesis requirements of Iowa State University

Signature was redacted for privacy.

Major Professor

Signature was redacted for privacy.

For the Major Program

Signature was redacted for privacy.

For the Graduate College

DEDICATION

This work is dedicated to three people who have supported me during the most difficult time in my life. The first is my mother, Dorothy Sargent, who for 34 years has shown me what love and patience truly mean. The second is my major professor, Todd Sandler, who became like a foster parent to me during my hospitalization. Had it not been for him, I might not be walking on two feet today. His encouraging visits, phone calls, and E-mails never failed to boost my spirits when I needed it. The third is my best friend, Tzu-Ling Huang, whose continued love throughout my accident and recovery have shown me that the reasons I am loved have nothing to do with my feet.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ACKNOWLEDGMENTS

My thanks and gratitude go to my major professor, Todd Sandler, for his patience, understanding, and encouragement for over five years. His classes inspired me to choose public goods as one of my fields and his enthusiasm for the subject has rubbed off on me. Todd's moral and intellectual support and faith in me, both before and after the accident, have helped me to believe more in myself and my capabilities. Todd is a great counselor and therapist; economics is only one of his many talents.

My thanks and acknowledgments also go to each and every member of my committee. Noel Cressie's book on spatial statistics helped open a new world for me, and his comments on my dissertation helped me navigate that world. The classes taught by Cathy Kling and Joe Herriges whetted my interests in environmental economics and their insightful comments on my dissertation have improved it. Last but not least, I wish to thank Arne Hallam for the books he lent me, the classes that challenged me, and the spiritual encouragement he gave me during my recovery.

Much gratitude also goes to those who were responsible for my continued funding in the department, in spite of the uncertainty of when I would return: John Miranowski, Charlene Carsrud, Harvey Lapan, Arne Hallam, and Todd Sandler. I would also like to thank all the people who kept up my spirits in the hospital with their E-mail and their visits, and the dinners and other help they gave me after I returned, but was still not very mobile: Fran Antonovitz, Fang Cai, Victor Chan, Aju Fenn, Frank Fuller, Rick Hawkins, Janice Holtcamp, Naoki Ito, Anna Kolbasova, Koji Kondo, Shimanto Mitra, Jeannie Panther, Genevieve Signoret, Kevin Siqueira, George Warren, and Bob Wilhelmi.

ABSTRACT

This dissertation develops a theoretical model that explains differences in emission reductions of transboundary air pollutants among nations based on national income, political freedom, the cost of emission reductions, emissions from other countries, the type of pollutant, and the pollutant's dispersion characteristics. The model is based on the theory of the private provision of impure public goods. This theoretical model is then used to derive a reduced form demand equation for emission reductions that can be econometrically estimated using spatial autoregressive techniques that have been modified to use time-series cross-section data.

The econometric model is applied to 25 European nations and covers the period from 1980 to 1990. These 25 nations were signatories to the Helsinki Protocol of 1985, which mandated reductions in sulfur dioxide (SO_2), and the Sofia Protocol of 1988, which limited emissions of nitrogen oxides (NO_x). The signing of these treaties indicated a recognition of the problems caused by acid rain and ozone pollution, yet the two treaties had very different requirements regarding emission reductions, and in addition, nations were much more likely to meet the requirements of the Helsinki Protocol than the Sofia Protocol. By taking into account the differences between nations and the different characteristics of the pollutants, my model allows a closer examination of the reasons for the differences in treaty requirements and treaty adherence.

The regression results can answer the following questions. First, did a nation's behavior change after a treaty was signed? Second, which factors were most important in determining the level of emission reductions? Third, what difference does the pollutant type make in determining the level of emission reductions?

Results based on pre- and post-treaty data for SO_2 and NO_x emission reductions indicate that nations follow a Nash-subscription model in choosing their emission reductions. In other words, nations tend to free ride on the emission reductions of other nations. The spatial autoregressive model performs convincingly for sulfur, showing in addition, that national income, the degree of political freedom, the percentage of a nation's emissions deposited on itself, and several other variables have a significant influence on the level of emission reductions. The model for NO_x is less satisfying. While nations continue to exhibit Nash behavior, the other variables fail to be significant or have the wrong sign. It turns out however that these results may be explained as resulting from the characteristic nature of NO_x as compared with sulfur. NO_x diffuses more rapidly in the air, stays up longer, and originates from a larger number of sources making it harder to control. Furthermore, nations are less likely to experience the harmful nature of their own NO_x emissions.

A better understanding of the factors that influence a nation's decision to reduce its emissions may provide a foundation for the negotiation of future transboundary pollution control treaties. New treaties could require some nations to make greater (or smaller) cuts in emissions, but by taking into account differences among the nations, larger total reductions and greater compliance might result.

CHAPTER 1. INTRODUCTION

Damage to the global environment is one of the most serious problems facing the world today; it is also one of the most difficult to solve. The land, sea, and air surrounding the planet is, in many ways, a global commons--a shared heritage of all humans. The tragedy of the commons discussed by Hardin (1968) thus applies on a global scale: the actions of a single nation may have effects felt worldwide to the detriment of all. And since it is unlikely that a sovereign nation will take full account of the effects of its actions on other nations, global externalities will often result. Furthermore, the global commons provides global public goods, such as the ozone layer, oxygen, fresh water, an hospitable atmosphere, and a storehouse of genetic knowledge. Olson (1965) showed that when collective action is needed to provide a collective good, the members of the group (i.e. the nations of the world) may fail to provide that good because the optimal behavior of a nation may not be the same as optimal behavior for the group. It is quite likely therefore, that there will be an underprovision of global public goods (such as preservation of biological diversity) and an overprovision of public bads (such as chlorofluorocarbons (CFCs), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and carbon dioxide (CO_2)).

Recognition of global commons problems led to several early global treaties such as the Nuclear Test-Ban Treaty in 1963, The 1972 Convention on the Prevention of Marine Pollution, and the 1973 Convention on International Trade in Endangered Species of Wild Flora. The number of global treaties signed and ratified has grown as new problems have been recognized (see Table 1.1).[1]

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., Barrett, 1993; Eyckmans, Proost, and Schokkaert, 1993; Helm, 1991; Herber, 1991; Runge, 1990, 1993; Sandler and Sargent, 1995; and Murdoch and Sandler, 1997b). This dissertation focuses on collective action problems concerning acid rain and surface-level ozone, stemming from the emissions of sulfur dioxide (SO_2) 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.[2] Likewise, world-wide concern over stratospheric ozone depletion led to the Convention for the Protection of the Ozone Layer, negotiated in Vienna in 1985. This convention paved the way for protocols that reduced and will, in the future, eliminate the production of CFCs.

The LRTAP Treaty

Covering 31 nations, LRTAP established a framework for future multi-national treaties. Currently, protocols to this treaty now cover sulfur emissions, nitrogen oxide

---

[1] A country is most likely to sign a treaty when the chief executive approves. Treaty ratification occurs only at the legislative level after the signing. Thus ratification is more legally binding on a country.

[2] See UN Environment Programme (1991) for treaty and protocol text.

Table 1.1. Selected Major International Environmental Treaties

Treaty	date	number of signatories	number of ratifiers	total
Antarctic Treaty (a)	1959	0	39	39
Nuclear Test Ban (b)	1963	11	109	120
Wetlands (c)	1971	1	83	84
Biological and Toxin Weapons (d)	1972	18	104	122
World Heritage (e)	1972	2	118	120
Ocean Dumping (f)	1972	14	59	73
Endangered Species (CITES) (g)	1973	5	106	111
Ship Pollution (MARPOL) (h)	1978	0	65	65
Migratory Species (i)	1979	10	37	47
Transboundary Air Pollution (j)	1979	0	38	38
Antarctic Living Marine Resources (k)	1980	0	27	27
Law of the Sea (l)	1982	86	40	126
Ozone Layer (m)	1985	1	102	103
Nuclear Accident Notification (n)	1986	24	56	80
Nuclear Accident Assistance (o)	1986	26	56	82
CFC Control (p)	1987	2	94	96
Hazardous Waste Movement (q)	1989	24	34	58
Biodiversity (r)	1992	120	23	143
Climate Change (s)	1993	113	27	140

Source: World Resources Institute (1992, Table 25.1 and Table 25.2); World Resources Institute (1994, Table 24.1 and Table 24.2); United Nations (1993, Table 6)

(a) The Antarctic Treaty (Washington, D.C., 1959).

(b) The Treaty Banning Nuclear Weapons Tests in the Atmosphere, in Outer Space, and Under Water (Moscow, 1963).

(c) The Convention on Wetlands of International Importance Especially as Waterfowl Habitat (Ramsar, Iran; 1971).

(d) The Convention on the Prohibition of the Development, Production, and Stockpiling of Bacteriological (Biological) and Toxin Weapons, and on their Destruction (London, Moscow, Washington, D.C., 1972).

(e) The Convention Concerning the Protection of the World Cultural and Natural Heritage (Paris, 1972).

(f) The Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London, Mexico City, Moscow, Washington, D.C.; 1972).

(g) The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (Washington, D.C.; 1973).

(h) The Protocol of 1978 Relating to the International Convention for the Prevention of Pollution from Ships, 1973 (London, 1978).

(i) The Convention on the Conservation of Migratory Species of Wild Animals (Bonn, 1979).

(j) The 1979 Convention on Long-Range Transboundary Air Pollution (LRTAP).

(k) The Convention on the Conservation of Antarctic Marine Living Resources (Canberra, 1980).

Table 1.1. (continued)

(m) The Vienna Convention for the Protection of the Ozone Layer (Vienna, 1985).
(n) The Convention on Early Notification of a Nuclear Accident (Vienna, 1986).
(o) The Convention on Assistance in the Case of a Nuclear Accident or Radiological Emergency (Vienna, 1986).
(p) The Protocol on Substances that Deplete the Ozone Layer (Montreal, 1987).
(q) The Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and their Disposal (Basel, 1989).
(r) The Convention on Climate Change (New York, 1993).
(s) The Convention on Biological Diversity (Nairobi, Kenya; 1992).

emissions, and volatile organic compounds (see Table 1.2 for the treaty and protocols relevant to the study of sulfur and nitrogen oxide emissions). The LRTAP Convention was adopted on 13 November 1979 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). The signatories of LRTAP agreed 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.

Table 1.2. The 1979 LRTAP Convention and its Related Protocols

Country	Convention (a)	EMEP Protocol (b)	Sulfur Protocol (c)	NOx Protocol (d)
Albania				
Austria	1982 R	1987 Ac	1987 R	1990 R
Belarus	1980 R	1985 At	1986 At	1989 At
Belgium	1982 R	1987 R	1989 R	1988 S
Bosnia and Herzegovina	1993 R	1993 Sc		
Bulgaria	1981 R	1986 Ap	1986 Ap	1989 R
Canada	1981 R	1985 R	1985 R	1991 R
Croatia	1992 Sc	1992 Sc		
Cyprus	1991 Ac	1991 Ac		
Czechoslavakia	1983 R	1986 Ac	1986 Ap	1990 Ap
Czech Republic	1993 Sc	1993 Sc	1993 Sc	1993 Sc
Denmark	1982 R	1986 R	1986 R	1993 At
Finland	1981 R	1986 R	1986 R	1990 R
France	1981 Ap	1987 R	1986 Ap	1989 Ap
Germany	1982 R	1986 R	1987 R	1990 R
Germany, East	1986 Ac		1985 S	
Greece	1983 R	1988 Ac		
Hungary	1980 R	1985 Ap	1986 R	1991 Ap
Iceland	1983 R			
Ireland	1982 R	1987 R		
Italy	1982 R	1989 R	1990 R	1992 R
Liechtenstein	1983 R	1985 Ac	1986 R	1994 R
Luxembourg	1982 R	1987 R	1987 R	1990 R
Netherlands	1982 At	1985 At	1986 At	1989 At
Norway	1981 R	1985 At	1986 R	1989 R
Poland	1985 R	1988 Ac		
Portugal	1980 R	1989 Ac		
Romania	1991 R			
Russian Federation	1980 R	1985 At	1986 R	1989 At
Slovakia	1993 Sc	1993 Sc	1993 Sc	1993 Sc
Slovenia	1992 Sc	1992 Sc		
Spain	1982 R	1987 Ac		1990 R
Sweden	1981 R	1985 R	1986 R	1990 R
Switzerland	1983 R	1985 R	1987 R	1990 R
Turkey	1983 R	1985 R		
Ukraine	1980 R	1985 At	1986 At	1989 At
United Kingdom	1982 R	1985 R		1990 R
United States	1981 At	1984 At		1989 At
Yugoslavia	1987 R	1987 Ac		

Source: United Nations (1993, Table 6); United Nations (1994, private correspondence with the Treaty Section).

Table 1.2. (continued)

(a) Convention on Long-range Transboundary Air Pollution, adopted 13.11.1979, entered into force 16.3.1983.
(b) Protocol to the 1979 Convention on Long-range Transboundary Air Pollution on Long-term Financing of the Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe (EMEP), adopted 28.9.1984, entered into force 28.1.1988.
(c) Protocol to the 1979 Convention on Long-range Transboundary Air Pollution on the Reduction of Sulfur Emissions or their Transboundary Fluxes by at least 30 percent, adopted 8.7.1985, entered into force 2.9.1987
(d) Protocol to the 1979 Convention on Long-range Transboundary Air Pollution concerning the Control of Emissions of Nitrogen Oxides or their Transboundary Fluxes, adopted 31.10.1988, entered into force 14.2.1991.
(e) Protocol to the 1979 Convention on Long-range Transboundary Air Pollution concerning the Control of Emissions of Volatile Organic Compounds or their Transboundary Fluxes, adopted 18.11.1991.

R = Ratified; Ac = Acceded; Ap = Approved; At = Accepted; Sc = Succeeded; S = Signed.

In the case of NO_x emissions, protocols have been much slower. On 31 October 1988, the Sofia Protocol was signed, requiring reductions in NO_x to return to 1987 levels by 31 December 1994 (UNEP, 1991). This protocol did not enter into force until 14 February 1991.

The protocols to the LRTAP convention were designed to reduce or stabilize emissions of sulfur and NO_x. These emissions combine in the atmosphere with water vapor and tropospheric ozone, producing sulfuric and nitric acid. These acids can later fall with the rain and degrade lakes, rivers, coastal waters, forests, and manmade structures. This degradation can also stem from dry depositions of sulfur and NO_x that lead to increased acidity of soils and water sheds. 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 (OECD, 1990). 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 the interpretation of the empirical results in later chapters (see Figure 1.1).

In addition to acid rain, sulfur and NO_x emissions lead to reductions in ambient air quality that may cause serious human health impairments to susceptible populations -- particularly the young and old. NO_x and volatile organic compounds (VOCs) are the primary precursors to tropospheric ozone in European cities (OECD, 1990). Ambient levels of particulate matter (PM), which are potentially more damaging than tropospheric ozone, are also influenced by sulfur and NO_x emissions. Approximately 10 percent of emitted SO_2 is converted to airborne sulfate aerosol (Latimer, Iyer, and Malm, 1990), and up to 20 percent of the total PM mass is attributable to sulfates (Sisler et al., 1993). Similarly, some fraction of NO_x is converted to nitrates which comprise up to 5 percent of PM mass. Given that recent epidemiology studies have found a consistent association between premature death and PM (e.g., Schwartz, 1991), ambient and deposition aspects of these pollutants cause harm.

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

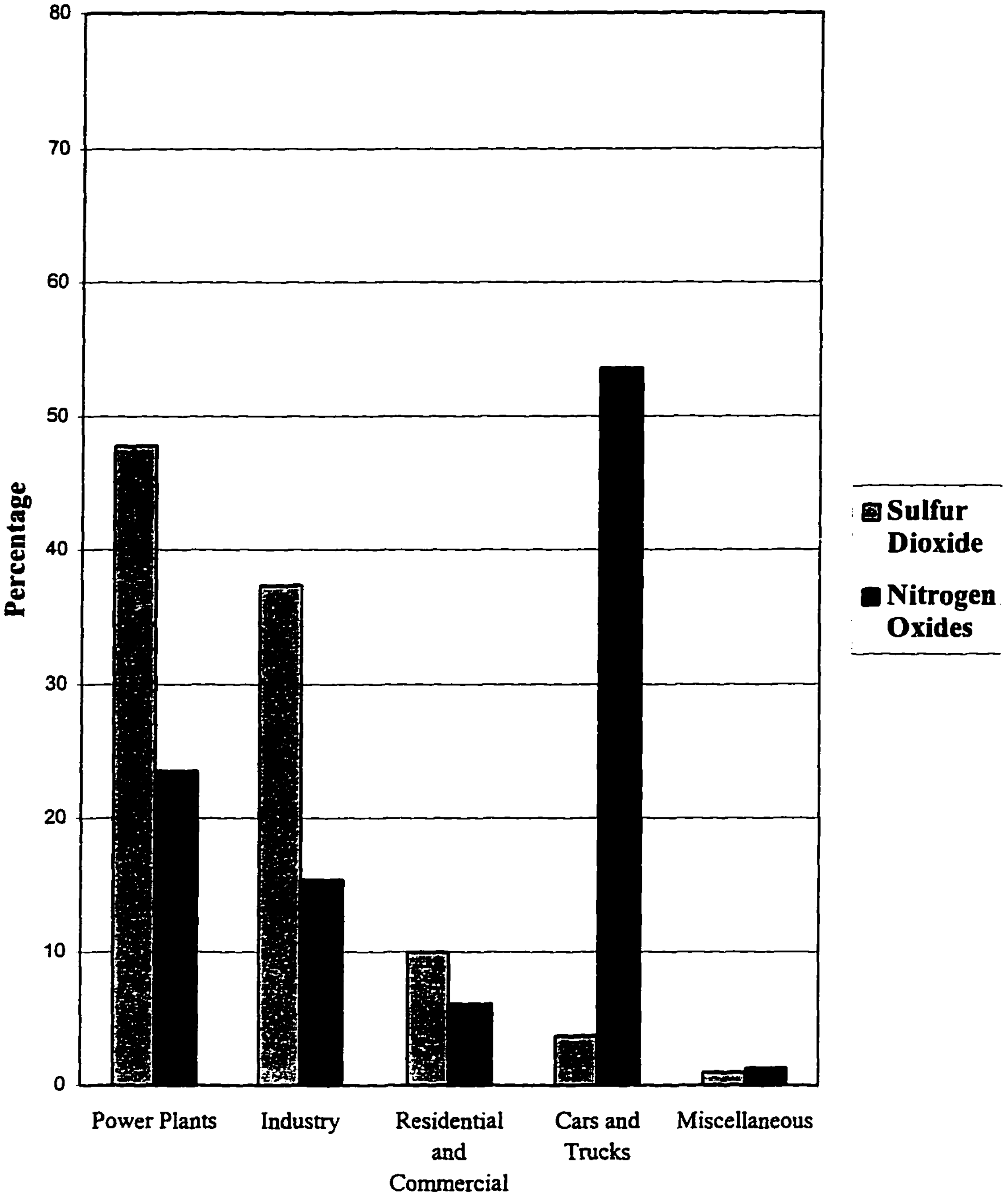

Figure 1.1. Sources of Emissions

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). Therefore, on average, sulfur pollutants travel shorter distances than NO_x pollutants and land nearer to home.[3]

To account for the transport of sulfur and NO_x among European countries, I rely on the transport matrix devised from EMEP measurements (Eliassen and Saltbones, 1983) and reported for various years in Sandnes (1993) and Tuovinen et al. (1994). For example, a sulfur matrix's entries indicate the amount of sulfur deposited in country i (row country) emitted by country j (column country). 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, a transport matrix results. Each entry of the transport matrix 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

---

[3] A longer unpublished version of this paper contains tables on the raw data and the transferability of the pollutants. See Murdoch, Sandler and Sargent (1994, Tables 1A-4A), which is available upon request.

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. The transport matrix for 1985 by Sandnes (1993) is used in chapter 4, while the empirical model in chapter 5 uses an averaged 1985-93 transport matrix by Tuovinen et al. (1994).

A decrease in ambient air quality is related to depositions, since PM is proportional to emissions, and ambient impacts are experienced as pollutants are transported to their sites of deposition. I must rely on EMEP's deposition transport matrix to represent ambient transportation, inasmuch as data is not directly available for this transport for the sample period or countries. Surely, ambient air quality is reduced in and around deposition sites. I should, however, point out that the concern over ambient aspects of sulfur emissions is a recent phenomenon and did not characterize the period under study. Nevertheless, I attempt to include its effects on the demand for emission cutbacks.

The Problem

While the protocols covering sulfur, nitrogen oxides, and CFCs are similar in that they legally bind nations to limit or reduce transboundary air pollutants, the differences between the requirements are striking. Specifically, the update to the 1987 CFCs (or Montreal) Protocol required a 50% cutback in the production and consumption of CFCs by 1998 based on 1986 levels. This was strengthened three years later so that the same level of reductions had to be completed by 1995. An outright ban on the production of CFCs will go into effect on 1 January 2000. These requirements can be contrasted with those of the Sulfur (or Helsinki) Protocol which mandated nations by 1993 to reduce their sulfur emissions by 30% based on 1980 levels, and the Nitrogen (or Sofia) Protocol which required nations to limit their nitrogen emissions by 1995 to the emission levels of 1987.

Why is it that nations have committed to making dramatic reductions in CFCs, moderate reductions in sulfur emissions, and so little reduction in nitrogen emissions? This dissertation will examine how the technology of public supply plays an important part in determining the nature of the cutbacks. For example, while the ozone shield is a pure public good, with most nations affected equally by its loss, acid rain (caused by sulfur and nitrogen emissions) has more localized effects. Through chemical reactions occurring in the atmosphere, these two pollutants are the main contributors to acid rain, an impure public bad. Nations closest to the largest emissions are subject to the highest levels of pollutant and often suffer the greatest damage from acid rain. Thus the technology of public supply for pollutants that cause acid rain is very different from the technology of public supply for the pollutants that cause the thinning of the ozone layer. As I will show, this difference appears to have influenced the requirements contained in the treaties that govern these pollutants.

But an additional question beyond differences in emission cutbacks presents itself: have nations by cooperating together made cutbacks that go beyond what they would have achieved if they had acted separately? In other words, have the nations truly cooperated to achieve lower levels of emissions, or have they simply signed treaties that confirmed reductions that were already made or that they had planned to make? This dissertation will show how group size, heterogeneous payoffs, and transactions costs are crucial in determining the actions of nations, and how close these actions are to an optimal solution. Nations are more likely to cooperate when the number of ratifiers is small, when transactions costs are low, when certainty is high, and when there are large private benefits relative to public benefits.

Since each of the protocols under discussion mandates all nations to make identical percentage cuts in their emissions, it is unlikely that all nations acting alone would have made the same level of reductions[4]. But it is also unlikely that the cooperative solution would have resulted in identical percentage cutbacks. In fact the recently signed Oslo Protocol makes it clear that equal percentage reductions are not an optimal solution to controlling acid rain. Instead this treaty emphasizes the need to stay below critical levels--the level at which damage begins to occur to a nation's ecosystem from a pollutant. This critical level varies among nations. Likewise, it is recognized that nations have differing pollution control costs and that negotiation and side payments may be needed for an optimal least-cost solution. An optimal solution for controlling transboundary pollutants will, therefore, require international coordination. But the differing costs of emission reductions, and differing levels of damage from pollutants among countries means that the true cooperative solution (taking full account of the costs and benefits) will require some nations to make larger reductions than others.

---

[4] Side payments, such as those used in the Montreal Protocol, to countries with higher control costs can be an efficient mechanism to achieve similar reductions among countries.

Because the theoretical and empirical focus of this dissertation is on what factors determine a nation's contribution to impure public goods, there is also a need to find out how close nations are to achieving a cooperative solution. One way to help answer these questions empirically is to use a numerical method that can represent both the technology of public supply of a good and the amount of public and private benefits that result from a nation contributing to that public good. A spatial weight matrix performs this task very well. The numbers inside the matrix are determined by the "spillovers" of a public good from one region into another (the spillovers, can either be represented in absolute terms or percentages). The two-dimensional matrix consists of the contributing regions on one axis and the receiving regions on the other axis (for simplicity, the matrix uses the same regions on both axes).

Such a matrix is quite useful in examining global (and even local) public goods. A pure public bad, like CFCs, which affects all nations equally, would result in a spatial matrix of all ones (i.e. 100 percent) since the damage done by the public bad affects everyone equally.[5] On the other hand, a matrix for an impure public bad, such as sulfur, would be a nonsymmetric matrix with the values of the elements determined by total emissions, the amount of time the pollutant stays airborne, the location of the sources of emissions, and wind direction among the regions.[6]

---

[5] In contrast, a private good would have a spatial weight matrix (in percentage terms) with ones along the diagonal and all the non-diagonal elements equal to zero, since only the contributing nations receive benefits from the good.

[6] If the matrix is expressed in percentage terms, it would still be nonsymmetric and the values of the elements would range between zero and positive one.

The spatial weight matrix can be separated into two different matrices. One diagonal matrix, A, composed of only the diagonal elements of the weight matrix, with zeros on the off diagonal, indicates the percentage (or amount) of a nation's emissions that falls on itself. Another matrix, Ã, with zeros along the diagonal, but all other elements identical to the elements in the weight matrix, indicates the distribution of one nation's emissions falling on all other nations. If the A matrix is added to the Ã matrix, the result is the original matrix.

The field of spatial statistics provides a method, spatial autoregression, that uses the spatial weight matrix as an independent variable in a regression yielding consistent and unbiased estimates for all the independent variables. The resulting coefficient and standard error for the spatial weight matrix indicate the importance of public supply technology and how the distribution of benefits influences contributions to the public good.

If the emission reductions of a country are positively influenced by the amount of the country's emissions deposited on itself and on its neighbors, ceteris paribus, then it is behaving cooperatively. If however, a country reduces its emissions only to reduce the damage its emissions cause to itself, then it is not behaving cooperatively. For example, the results of a spatial regression examining the behavior of an altruistic nation would show positive coefficients for both the A and Ã matrices since that nation is concerned about the health of its citizens and its forests, but also the health of citizens and forests of other nations. A purely selfish nation would have a zero or negative coefficient for the Ã matrix, since that nation is either not concerned with the amount of its pollution that falls on its neighbors (indicated by a zero coefficient), or it decreases its emission reductions if it sees that less pollution from others is landing on its own soil (indicated by a negative coefficient).

Outline of the Dissertation

The body of the dissertation consists of six chapters. Chapter 1 consists of an introduction to the dissertation and background information on the problem of air pollution in Europe. In chapter 2, the existing literature on the provision of public goods is reviewed. The review begins with pure public goods models and is extended to the joint products model. This is followed by an examination of the relationship between public goods and military alliances which share problems similar to those encountered by countries negotiating transboundary treaties. The final part of chapter 2 examines existing literature on international environmental agreements.

Chapter 3 focuses on the formation of treaties to manage transnational commons when efforts must be coordinated among a minimal-sized group so as to make cooperation worthwhile. Since the intentions of the others in the group are uncertain, the focus is on the use of mixed-strategy equilibria. The number of required participants, the pattern of payoffs, transaction costs, and the underlying technology of public supply aggregation are key factors behind the achievement of coordination. The last part of the chapter analyzes the reasons for the differing outcomes of negotiations on stratospheric ozone depletion, global warming, acid rain, and tropical deforestation.

In chapter 4, a subscription model of emission reductions is specified that accounts for voluntary and nonvoluntary behavior regarding the adherence to the Helsinki and Sofia Protocols. From this model, two reduced form demand equations for emission reductions are developed using spatial econometric techniques--one model for sulfur and one model for nitrogen oxides--that account for the spatial dispersion of each type of pollutant. Data from 25 European nations and covering the years 1980 to 1990 will be used in the models. The models for sulfur reductions first examine changes in SO_2 emission reductions during the pre-Helsinki period (1980 to 1985), which are strictly voluntary, and then examine voluntary SO_2 emission reductions that occured after the Helsinki Protocol (but which use 1980 as the base year to calculate emission reductions up to 1990). For nitrogen oxides, the models use voluntary emission reductions in the pre-Sofia period (1980 to 1987) and the post-Sofia period (1988 to 1990).

In the sulfur model, the first time period describes a country's voluntary behavior before the treaty was signed, while the second describes the post-treaty non-voluntary behavior. For the nitrogen oxide model the treaty had not taken effect (i.e. been ratified) but it is reasonable to test for a difference in emissions between the two time periods mentioned because of the signing of the treaty in 1987.

Comparing the results between the two periods will give information on whether a treaty had a significant effect on a nation's level of pollutant emissions. If treaties simply codified emission reductions that countries had planned to make, based on their own self-interest, then pre- and post-treaty behavior should not significantly differ from each other.

In such a case, treaties were not designed to achieve a cooperative solution to transboundary air pollution, but rather to score political or public relations points at the domestic and/or international level.

By comparing the regression results between the two models, the influence of public supply technology (that is, the degree of publicness of a transboundary pollutant) on pre- and post-treaty behavior will be shown. Since sulfur and nitrogen emissions have different degrees of publicness, some differences between the two models should occur. In addition, countries are expected to depart further from the cooperative solution in both pre- and post-treaty periods because nitrogen oxides have longer atmospheric residence times than sulfur (that is, it is easier to send your nitrogen emissions over to your distant neighbor).

The model performs well for SO_2 cutbacks. Less satisfying results are obtained for NO_x, because the model's assumption of a unitary actor at the national level is less descriptive. A number of collective action considerations are identified that indicate that sulfur emissions are easier to control than those of NO_x.

Chapter 5 examines the behavior of the 25 European nations using a more advanced econometric model than the model used in chapter 4. This model, a spatially-lagged Seemingly Unrelated Regression (SUR) model, allows a year-by-year comparison of the determinants of SO_2 and NO_x emission reduction from 1980 to 1990. The Nash-subscription model again serves as the theoretical model for deriving each year's reduced form demand equations for voluntary emission reductions.

Comparing the results of the "snapshot" models of chapter 4 to the "continuous" models of chapter 5, allows a more detailed analysis and gives some idea of how robust the models are. In addition, the extra degrees of freedom provided by the continuous model allows one to examine more variables and track their effects over time. In both the sulfur and NO_x models, there is evidence that the influence of certain variables changes over time. Some variables that were significant in the snapshot model, turn out to be significant in some years but not in others in the continuous model. There are several possible explanations for these changes including "noisy" variables, increasing scientific knowledge, and shifts in political ideology.

Overall, the subscription model for sulfur reductions works as well for the yearly cases as it did for the snapshot cases. The results also appear robust since most variables are significant and of the predicted sign in the pre- and post-treaty years for voluntary sulfur emission reductions. Again, however, the results of the NO_x models are less satisfactory. But, as in the snapshot models, the yearly models indicate that nations continue to free-ride off the reductions of others' sulfur and NO_x emissions.

In the concluding chapter, I summarize the main findings of my dissertation, review the importance of these results and their relationship to the theory of public goods models, and examine how these findings can be used to improve future transboundary pollution control treaties. Finally, I identify the future areas of research that this dissertation points toward.

CHAPTER 2. LITERATURE REVIEW

Introduction

Transboundary air pollution is an externality with the characteristics of either a pure or impure public bad. Samuelson (1954, 1955) formalized the ideas of earlier authors (such as Lindahl and Wicksell) on the optimal provision of pure public goods by deriving the first-order conditions for a Pareto optimum. However, economic literature on achieving efficient amounts of externalities began with Pigou (1946) who discussed how taxes and subsidies, if properly allocated, could internalize an externality and thereby achieve Pareto optimality.

Samuelson dealt with the simplest type of externality, that of a pure public good. This type of good has benefits that are both nonexcludable and nonrival; in other words, one cannot prevent others from deriving benefits from the good once provided, nor can an individual who partakes of the benefits of a public good diminish the quantity of the public good available to others.

Transboundary air pollution is certainly nonexcludable--once in the air, no nation can erect a barrier to exclude itself from the effects of the pollution. However, only some types of air pollution have effects that are nonrival. For example CO_2, which influences earth's temperature, and CFCs, which have been shown to cause depletion of the ozone layer, are nonrival public bads. That is, each unit of the pollutant causes atmospheric effects that will eventually be felt around the world. Furthermore, the effects on a particular nation are independent of the number of units that nation contributed. Instead, national damage is determined by total world emissions.

On the other hand, sulfur dioxide (SO_2) and nitrogen oxides (NO_x) are impure public bads. Although they possess the property of nonexcludability, they are only partially nonrival. Each unit of pollution that lands on one nation, is one less unit that will land on another nation, but the amount of acid rain that falls on a country is determined by that country and its neighbors. It is possible to model these types of pollutants within the framework of a joint product model--an externality that has both private (country-specific) effects and public (world-wide) effects (Sandler, 1992). Country-specific effects include reduced damage to buildings and works of art, increased fish catches in rivers and lakes, and fewer health problems in cities. Public good aspects, confined mostly to the continents, would include greater biodiversity in forests, watershed protection, and greater recreation opportunities.

The pure public good subscription model is the most common model used in studying the allocation of public goods. In this model, each agent seeks to maximize his or her utility subject to a budget constraint. Utility is a function of the consumption of a private good and the total amount of public good provided. Agents purchase the private good and choose the amount they wish to contribute to the public good.

In the most common scenario, agents assume that their contribution to a public good has no effect on the amount of the public good provided by other agents. The resulting equilibrium is referred to as the Nash, noncooperative, zero-conjecture, or subscription equilibrium. The Nash equilibrium will, in most cases, fall short of the Pareto optimal level.[1] This is not surprising since each agent ignores the effects of their own contribution on others' utility. For many types of utility functions (the Cobb-Douglas and quasi-linear among others), if tastes and endowments are the same for all agents, the shortfall between the Nash equilibrium and the Pareto optimum will increase as group size increases (Cornes and Sandler; 1996, 161-163). This result corresponds to Olson's (1965) hypothesis that free-riding increases with group size.

The simple pure public good model may be extended in two ways: first, by incorporating non-zero conjectures into the agent's reaction function, or second, by taking account of public goods that generate multiple outputs. Cornes and Sandler (1984b) developed a functional form that allowed different conjectural variations to be investigated by varying a single parameter. Depending on this parameter, the equilibrium solution may converge to Nash as group size increases or may become Pareto. Cornes and Sandler find that the "Olson conjecture" holds in many cases. These solutions assume that the agents are identical in terms of tastes and endowments. When agents are not identical, it is impossible to say a priori how far the non-Nash equilibrium departs from the Pareto solution. Such a situation would occur if some agents regard the public good as a bad. For example, a pacifist would likely regard defense spending as a public bad.

In the second extension of a pure good model, one recognizes that a good or activity may generate multiple outputs and these outputs may be private, purely public, or

---

[1] This assumes that all agents regard the public good as having a positive marginal utility.

impurely public and so a joint product (or impure public good) model is appropriate. In fact the joint product model is an extension of the pure public good model that allows for multiple public goods. Any type of externality problem can be represented by this model (Cornes and Sandler, 1984a). In the case of multijurisdictional spillovers, which occur in both defense spending among allies and transboundary air pollution, each jurisdiction chooses to supply a quantity of the public good based upon the amount of spillover from other jurisdictions. The response to the spillover, that is the stability of the production reaction path, will depend upon both the income elasticity and the degree of complementarity/substitutability of the joint products (Sandler and Culyer, 1982). In contrast, when there are no joint products, the stability and slope of the reaction path are determined only by the income elasticities of the private and public goods. In fact, a joint product model that deals with normal goods will generate reaction curves that are positively sloped if the substitution effect is in the same direction as the income effect. In other words, an increase in the total amount of the public good will cause a player to increase their own public good contribution. This is not possible in a pure public good model with only two goods (Cornes and Sandler, 1994).

Another important difference between the pure public good model and the joint product model occurs when examining the Neutrality theorem or Invariance property discussed by Warr (1983). In a pure public good model, under certain conditions, it is impossible to provide more of the public good by taxation or by redistributing income among a group of contributors, assuming the group of contributors remains unchanged

(Bergstrom, Blume, and Varian; 1986). But this result does not necessarily hold for joint product models (Cornes and Sandler, 1984a; 1985; Sandler and Posnett, 1991). Therefore, tax and redistributive properties may have important effects on the provision of impure public goods.

Public Goods and Military Alliances

The subject of defense expenditures among allies has been one of the most productive areas for studying the provision of international public goods. Like transboundary air pollution, defense spending has both private aspects (e.g., maintenance of domestic order, disaster relief) and public aspects (e.g., deterrence). A public good supplied by one nation will result in "spillovers" or "spillins" that will benefit other members in the collective, to varying degrees. For example, if a large nation and a small nation are allies, then the larger nation's army will deter other countries from attacking its smaller ally; therefore, the smaller nation can spend less on its military forces and still have a higher level of security, compared to a nonallied situation. Likewise, in the case of transboundary air pollution, when a nation reduces its own emissions, the nations bordering that nation gain some of the benefits (spillovers) from cleaner air and may be less likely to reduce their own emissions.

Empirical work on the provision of public goods got a strong impetus from Olson's ground breaking study on collective action problems in 1965. In his book, Olson put forward many ideas about the causes and consequences of collective failure (summarized by Sandler, 1992). First, the larger the membership of the group, the greater will be the departure from the Pareto optimal provision of the public good.[2] Second, the smaller members of a group (i.e. those with fewer resources) will have a tendency to exploit or "free-ride" on the contributions of the larger members. Third, selective incentives and institutional design may reduce collective failures.

Olson and Zeckhauser (1966) were the first to formally study alliance behavior using a public goods model. They were interested in testing Olson's hypothesis of free-riding in a group. Using NATO alliance members, they assumed that each country maximized its utility by consuming a private and a public good subject to a national budget constraint. Olson and Zeckhauser conceived NATO as sharing a pure public good--nuclear deterrence. The benefits from a nation providing such a good spill over to other members of the alliance. Olson and Zeckhauser found that spillins will often cause an ally to cut its own defense spending and that the response to spillins depends only on income elasticity. Thus a nation's wealth determines its level of public good provision. One of the limitations of the Olson and Zeckhauser model was, however, that it only allowed two goods. When the model is extended to account for joint products, the results change. Sandler and Forbes' (1980) joint product model found that wealth was not the only determinant of defense expenditures, while Murdoch and Sandler (1982) showed that if defense goods are complements, allies may actually increase defense expenditures as other

---

[2] A Pareto optimal point is one where it is not possible to make someone better off without making another worse off. Social optimality does not necessarily imply Pareto optimality. In fact, there are many Pareto optima, but only one of these can be the social optimum. In order to identify this point, a social welfare function is needed.

nations increase theirs. Such behavior is not possible in a two good model because the goods are forced to act as substitutes (Hicks, 1946).

But can emission reductions be compared with military deterrence? Are emission reductions complements or substitutes? The answer may depend on the shape of the damage function which tells how the environment is affected by different levels of pollution. With a linear damage function, it would be logical to expect emission reductions to behave as substitutes. Spillovers (of reduced emissions) from one nation, allow other nations to increase their emissions and still achieve the same level of environmental quality. On the hand, if there are other considerations (such as reputation) involved, then the result may not be clear-cut. It may be difficult for one nation to be seen as a "dirty" nation if all nations around are "green." If this is true, then something like leader-follower behavior may occur, as one nation, perhaps the largest, sets an example that others follow.

A damage function may be discontinuous (i.e. there may be a threshold effect) or non-linear. The shape of the function may also determine the degree of complementarity-substitutability depending on the level of pollution. Below the threshold, there will be no relationship between spillovers and a nation's own actions. Beyond a level of maximum damage there may again be no relationship or a positive one, since any pollution control will reduce GNP with only a marginal change in environmental quality. The damage function will thus create a problem for estimating whether emission reductions behave as complements or substitutes.

Returning to empirical studies, I note that it is also possible to model collective action questions with something other than the oligarchy choice models used by Olson and Zeckhauser. Using public choice theory to explain variations in the share of GNP devoted to military expenditures, Dudley and Montmarquette (1981) developed a new type of model. Using a Stone-Geary utility function[3] subject to the budget constraint of a median voter, they were able to estimate a demand function for per capita defense spending. Using full information maximum likelihood (FIML), to deal with non-linearities and simultaneity problems, the model was applied to 38 developed and developing countries separately for the years 1960, 1970 and 1975. Spillover effects were found to be significant and positive. Income elasticity and the tax price elasticity of demand were found to be significant. They could not reject Olson and Zeckhausers hypothesis of free-riding behavior among the smaller nations.

I have discussed two types of models used to examine collective action issues, oligarchy choice and median voter models. Murdoch, Sandler, and Hansen (1991) developed a nested test procedure that could distinguish between the two types of models. In a sample of ten countries in the NATO alliance between 1965 and 1988 they found some allies followed the median voter model while others followed the oligarchy choice model and others followed neither.

---

[3] The Stone-Geary utility function is simply a Cobb-Douglas function with its origin displaced. Thus it shares all the properties of the Cobb-Douglas function, including homotheticity. In addition it allows log-linear transformations to be represented as linear expenditure functions and forces budget shares to equal one when income changes.

Closely related to this idea, is the possibility that a nation's decision to contribute to a public good, particularly an environmental good such as emission reduction, will be influenced by the nation's political institution. Congleton (1992) shows that an authoritarian regime experiences a higher relative price for pollution control than a more democratic one (i.e. the median voter model). Since the leader consumes a larger national income share and has a shorter time horizon than his democratic counterparts, this causes him to desire a lower level of environmental quality because pursuing environmental quality takes time and may lower national output.

Olson (1993) also examines how the style of government affects public good provision. He hypothesizes that the tax rate will be higher and the level of public good provision will be lower in an autocracy than in a democracy. An autocracy will levy taxes at their revenue-maximizing level. This tax level is higher than the optimal tax rate which maximizes national output (assuming that all taxes collected in a democracy are used to purchase public goods which increase national output). In addition, the autocrat will spend money to provide a public good only up to the point where a dollar spent on the public good will yield a dollar increase in the autocrat's share of national output. Since the autocrat is only concerned with his share of national output rather than the level of output itself, the level of public good provision will be lower under the autocrat. Finally, Olson explains that since an autocrat has a shorter time horizon than a democracy, he will be less interested in policies that increase prosperity in the long run. His goal is to maximize his share of national output during his, probably brief, rule. This reinforces the above conclusions that taxes will be higher, and money spent on public goods lower, than they would be under a democracy.

It is also possible to investigate what type of cooperative strategy a nation follows in providing a public good. Sandler and Murdoch (1990) derived two alternative models that would distinguish between Nash and Lindahl behavior. Their results showed that in five of the ten NATO alliance members, the Nash specification fit the data best, while in no case did they find any evidence of Lindahl behavior.

While treaties forming military alliances have a long history (NATO itself is almost half a century old and for forty years has prevented a major European war), transboundary air pollution control treaties are of a more recent vintage. The relatively large number of nations (32) that have signed the LRTAP convention (about twice the size of the NATO alliance) raises questions about the effectiveness of transboundary air pollution control treaties. Since there is no international enforcement mechanism, it may be unlikely that any substantial gains would be made in pollution reductions beyond what nations would have done in the absence of the treaty. Barrett (1991) states that when the number of nations involved in international environmental agreements is large, very little can be achieved because an additional nation defecting or signing will have little effect on the decisions of others. Therefore, Barrett is skeptical that any dramatic gains were made by the Montreal Protocol. "...so many countries would not have committed themselves to the agreement in the first place unless they already intended to take substantial unilateral action." (Barrett; 1991, 150).

Murdoch and Sandler's (1997b) work empirically examines Barrett's claim. They showed that the theoretical model of the voluntary provision of a pure public good could be applied to a transboundary air pollution problem. They found that CFCs emission reductions could be explained by (1) national income, (2) political rights, and (3) geographical latitude. Using both parametric and nonparametric tests they were able to show that the cutbacks codified in the Montreal Protocol were consistent with self-interested (i.e. non-cooperative) behavior. This confirmed what Barrett (1992) had already suggested. In addition the model was able to distinguish between a pure public good (CFCs) and an impure public good with both private and public benefits (SO_2 emissions).

Finally, one may distinguish between different public supply technologies. Recently Conybeare, Murdoch and Sandler (1994) developed a method to differentiate between different technologies of public supply in military alliances. The authors extended the joint product model to include best-shot and weakest-link technologies and contrasted them with a simple summation technology. Examining four different alliances, they found one alliance (Triple Alliance prior to WW I) that appeared to exhibit best-shot behavior, one alliance (Triple Entente prior to WW I) conforming to weakest-link, while two other alliances, NATO and Warsaw Pact, were inconclusive.

In summation then, over the last thirty years a wealth of collective action models have arisen. The early pure public goods models were soon augmented by joint product models. The simple joint product models have been expanded to include cost differences among agents (McGuire, 1990), leader-follower behavior (Bruce, 1990), and median-voter theory (Dudley and Montmarquette, 1981; Murdoch, Sandler, and Hansen, 1991). A way to distinguish between cooperative and non-cooperative behavior was developed by McGuire and Groth (1985), and refined by Sandler and Murdoch (1990). And most recently, Conybeare, Murdoch, and Sandler (1994) developed a joint product model that can distinguish between different types of public supply.

Public Goods and Environmental Treaties

Although the literature on the public provision of environmental goods is not as extensive as that on the provision of military goods, there are some important works. One of the most important differences between a coalition of countries sharing military defense and an alliance of countries cooperating to reduce emissions of a pollutant, is the ability to punish defectors. Of course, the enforcement of an international treaty is not possible without some supranational organization that has been granted that right. However, in the case of a military alliance, the threat of being kicked out of the alliance is a greater deterrent for a potential defector than any type of threat that could be applied to the defector of an international environmental treaty. Specifically, a military alliance might be able to refuse to defend one of its members from attack, if that member were to repeatedly fail to meet its obligations to provide its share of the public good for the military alliance. Naturally the credibility of this punishment hinges on the amount of collateral damage that would result from an attack on its neighbor.

On the other hand, a nation that refuses to abide by a treaty limiting emissions of some pollutant, faces few sanctions from other members. To punish a member that defected from an emissions reduction treaty would involve increasing one's own emissions, thereby hurting oneself more than the defector, since one's own emissions are more harmful than that of a neighbor's. Alternatively, a group of nations might attempt to impose trade, financial, or diplomatic sanctions on a defector, but such sanctions are notoriously difficult to impose collectively. The only other possibility of punishing a defector from an environmental treaty would be refusing to defend that nation militarily. But for reasons already discussed, this is a credible threat only in a limited number of situations.

The ideal international environment agreement (IEA) would, therefore, be one that is self-enforcing. Barrett (1994) modeled IEA's as infinitely repeated games. The "folk-theorem" guarantees that such games can sustain full cooperation among any number of countries if the discount rate is not too small. Barrett examines how different marginal benefit and marginal cost curves affect this result. He found that for constant marginal benefits and logarithmic marginal costs, self-enforcing IEA's are limited to two countries; for linear marginal benefits and constant marginal costs self-enforcing IEA's do not exist. If marginal benefits are constant and marginal costs are linear, then self-enforcing IEA's are limited to either two or three countries. Finally, in the case of linear marginal benefits (which are assumed to be decreasing) and linear marginal costs (which are assumed to be increasing), the results depend upon the magnitudes and relative slopes of the two curves.

When the slope of the marginal cost curve (c) is small and the (absolute value of the) slope of the marginal benefit curve (b) is large then the gains from global cooperation are small but the private benefits of unilateral abatement are large. In this case, nations will undertake reduction cutbacks without any assurance that others will cooperate. There is little incentive to free-ride, but also little incentive to cooperate. On the other hand, with large c and small b, countries will not reduce emissions even if there is full cooperation among other countries, but little is lost since the global benefits of cooperation are small. If c and b are both small but about equal, then the difference in emissions between the cooperative and noncooperative solutions will be large but the gains from cooperation will be small. However if c and b are both large and about equal, then the difference in emissions between the cooperative and noncooperative solutions will also be large but the benefits from cooperating will also be large. Obviously, this last case is the most favorable for self-enforcing IEAs. Barrett's results are based on some rather stringent, and not particularly realistic, assumptions. First, all countries are identical. Second, each country's net benefit function is known by all other countries. Third, abatement levels are instantly and costlessly observed. And fourth, the benefit (demand) function is linear.

Barrett points out that for repeated games, the "folk theorem" may not hold even if the discount rate is small, since punishments cannot be enforced. This raises the issue Heckathorn (1989) refers to as the second-order free-rider problem. He points out that a system of punishments is just as much a public good, subject to free-riding, as is a public good like emission reductions. According to Heckathorn, cooperation arises in an iterated

Prisoner's Dilemma as a result of a sanctioning system that is created and enforced by group members that reward cooperation and punish defection. Therefore, each member of the group is faced with two questions: first, whether to cooperate at the first-level and provide the public good, and second, whether to cooperate at the second-level and participate in the system of sanctions. "Full cooperation" means to cooperate at both the first and second levels; "full defection" means to defect at both levels. A person choosing "hypocritical cooperation" defects at the first level but participates in the sanctioning system, while a "private cooperator" provides the public good but defects at the second level.

Heckathorn finds that private cooperation is optimal for small groups (less than or equal to two); full cooperation is optimal for group sizes from three to five; and hypocritical cooperation is optimal in group sizes greater than six. He finds that private and full cooperation are decreasing functions of group size (this reinforces Olson's hypothesis about the inverse relation between the provision of the public good and group size). Furthermore, no matter what the parameters are, "full cooperation is always less robust against increases in group size than is hypocritical cooperation."

The subjects of profitability and stability of international agreements are examined by Carraro and Siniscalco (1993). They define a coalition to be stable if no country has an incentive to defect from the coalition and no other country has an incentive to join (this appears identical to the definition of a self-enforcing treaty). The authors define four types of commitment that could serve as “blueprints for environmental cooperation.” These four types are less demanding than a commitment of full cooperation by all players, and may therefore be more useful when modeling international treaty formation. Another advantage is that they can serve as a springboard to more inclusive coalitions by the use of self-financed transfer payments to countries outside the coalition.

The first type of commitment, stable commitment, occurs when only the countries in the coalition cooperate. Sequential commitment, the second type, takes place when new members that enter a coalition start cooperating immediately. The third type is full cooperation with minimum commitment. This occurs when it is possible, by the use of appropriate transfers, to convince other nations to cooperate. External commitment is the last type of commitment and results if a subset of non-cooperating countries can redistribute wealth so that all other non-cooperators are persuaded to cooperate and that this coalition (of reluctant cooperators) is stable. The redistribution of wealth (i.e. transfer payments) has several restrictions. First, it must be self-financed from the expanded coalition. Second, the larger coalition must be Pareto Improving. And third, the redistribution is done to maximize the number of signatories.

Carraro and Siniscalco come to the surprising conclusion that when stable coalitions exist, the decision of whether a country should continue to cooperate, is not a Prisoner's Dilemma and so non-cooperation is not necessarily a dominant strategy. Moreover, they find that under reasonable specifications of the benefit and damage functions, stable coalitions for the protection of the environment exist.

Like Barrett, Carraro and Siniscalco show that it is the slope of the best reply function that is crucial for determining the effectiveness of cooperative and non-cooperative emission control. The more negative its slope, the greater is the incentive to defect from a coalition. In addition they find that if the best reply functions of two countries are orthogonal (or nearly so) then a coalition of those two countries can be stable since free-riders cannot offset the emission reductions of the group. In contrast, when the slopes of the best reply functions are negative, free riders will increase their own emissions offsetting the emission reductions of the group. There is an implied tradeoff here. Negatively sloped best-reply functions mean that nations can achieve substantial emission reductions but they have little incentive to cooperate with one another. In addition, free-riding will be a common problem. On the other hand, orthogonal or near orthogonal best-reply functions result in a strong incentive to cooperate with little incentive to free-ride but the reduction in emissions turns out to be small.

Three main conclusions emerge from their study. First, although there may be strategic interaction among countries when there is transboundary pollution, this does not necessarily lead to a "tragedy of the commons." There are instead a range of voluntary agreements possible to control emissions. Second, partial cooperative agreements that are profitable and stable exist among sub-groups of countries. Third, existing coalitions can be expanded by using the benefits from partial cooperation to finance welfare transfers. However, to sustain these larger coalitions, a minimum degree of commitment is required which, by definition, changes the rules of the game.

In “The Acid Rain Game” Mäler (1989) modeled emission reductions of sulfur as a game. He recognized that the acid rain problem has several important features. First, it is a game of incomplete information because the damaging effects of acid rain on human, health and the ecosystem are not known with certainty. Second, there are many players involved and they do not all agree on the rules of the game. And third, the distribution of the benefits from emission reductions (the public good in question) is asymmetric and can be represented by a spatial weight matrix.

Each country seeks to minimize the cost of emission control and the cost of the damage done to the country by emissions from itself and other countries. Mäler finds that a dominant equilibrium will exist only under the condition that the marginal damage function is constant and so is independent of the emissions of other countries. Second, only if countries have complete information on emissions, depositions, control costs, and damage costs will a Nash equilibrium exist. Mäler recognizes that in the real world there is unlikely to be a Nash equilibrium and that side payments may be necessary for a cooperative solution.

Mäler runs several numerical simulations for Europe to determine how far the existing situation departs from the full cooperative solution. Using estimates on control cost functions from the International Institute of Applied Systems Analysis (IIASA), the spatial weight matrix computed by the Co-operative program for monitoring and evaluation of the long range transmission of air pollutants in Europe (EMEP), and assuming a linear damage cost function, he first calibrates (or derives a baseline) model and compares the costs and benefits of that model with several alternative scenarios. He makes the following discoveries: The full cooperative solution would reduce total emissions of sulfur in Europe by about 40% but several countries would be worse off under this scenario and side payments would be needed to guarantee that these countries would join a treaty that called for such a level of emission reductions. If side payments were not possible, then the best solution would be a Pareto Dominating outcome. This situation reduces total benefits by about 6% from the full cooperative solution. The existence of a "strong equilibrium" (an equilibrium in which no coalition could gain by defecting against a coalition of all other countries) is unlikely in the European acid rain game because any member (or group of members) could do better on its own. Mäler points to the United Kingdom and Italy as two countries that always do better by staying out of a treaty that limits emissions. Both countries have high emission levels and experience few spills from other neighbors because of their geographic position and the prevailing wind patterns.

A different solution to the problem of transboundary pollution problems is proposed by Chichilnisky and Heal (1993). Although their paper appears more relevant to pure public bads (such as ozone layer depletion and global warming), there is no reason that it could not apply to other sorts of transboundary pollution. Rather than proposing the use of treaties with side-payments to insure cooperation among nations, they instead propose to expand existing financial and insurance markets.

According to Chichilnisky and Heal, the solution to the problems presented by global environmental risks, requires tools beyond those of classical formulations of uncertainty in economics. The risks of global climate change are different from the risks usually dealt with by economists because they are: (1) difficult to assess, (2) endogenous, (3) correlated, and (4) irreversible. Chichilnisky and Heal propose the use of Arrow-Debreu markets and insurance via risk-pooling to deal with the risk of global climate change. Under this method, agents would trade securities contingent on collective risks while mutual insurance contracts would cover the individual risks associated with changes in the global climate. In addition, this method gives a way for countries that differ in their assessment of risks to buy and sell securities based on this difference, protect themselves, and profit. This is an important result because even if there were agreement about the scientific facts of changes in the global climate, there might still be differences in the policy response.

Finally, I turn to the question of the qualities a model of transboundary air pollution should have. A useful model would distinguish between (1) a pure public and an impure public good, (2) the allocative process (i.e. Lindahl, Nash, or other), and (3) the institutional structure (median voter or autocracy). (see Sandler, 1992; chapter 5). But in addition the model would need to deal with the spatial dimension of air pollution. It is to this last topic that I now turn.

Public Goods and Spatial Econometrics

The very nature of transboundary air pollution suggests that there will often be a spatial aspect to the pollution unless it is a pure public good such as CFCs or greenhouse gases. If these spatial effects are not taken into account by the model, then the error term will exhibit spatial correlation and the parameter estimates will be biased and inconsistent (Anselin and Griffith, 1988). In a time series, the data are correlated across time, and in a spatial regression, the data are correlated across space. In both cases the data must be transformed to remove the correlation. Spatial autoregression transforms the data so that the error term is independent and normally distributed.

Although the first spatial statistic, the spatial autocorrelation coefficient, was developed by Student in 1907, it was not until the 1950s that spatial statistics were first put to extensive use by a geographer and statistician (Cliff and Ord, 1975). Since that time, the recognition of spatial correlation and use of spatial statistics has filtered into the economics profession and become more common. Granger (1969) recognized that it was "completely unrealistic" to assume spatial stationarity for economic variables. The extension of spatial autoregressive procedures into economics has been popularized by Anselin (1988) whose book, Spatial Econometrics: Methods and Models, serves as an excellent introduction to the subject, An excellent survey of the current literature on the analysis of spatial data can be found in Cressie's 1993 book: Statistics for Spatial Data. In addition, a special issue of Regional Science and Urban Economics vol. 22 (1992) was devoted to spatial statistics and econometrics.

Dubin (1988) developed a maximum likelihood method for estimating regression coefficients with spatial correlation in the error term and successfully used it in a hedonic regression of housing prices, later using the method to look at nighbohood quality (Dubin, 1992). The results showed a dramatic improvement over the use of ordinary OLS. Neighborhood variables and quality attributes became positive and significant, as one would expect. The bane of previous hedonic studies had been that the variables often had the wrong sign and were rarely significant.

Murdoch, Rahmatian, and Thayer (1993) used a spatial autoregressive term to analyze the spillins from an empirical estimation of a median voter model. They uncovered a relationship between recreation levels and ambient levels of air pollution. The spatial weight matrix consisted of the amount of recreation expenditures that spilled over into neighboring communities (both an inverse distance formula and a negative exponential distance formula were used to determine the elements of the spatial weight matrix). Since recreation services are an impure public good, the greatest benefit is derived by people living closest to the good with benefits trailing off as one moves further away. Another feature of a spatial weight matrix based on distance is that it is symmetric. This occurs because it should be just as easy for people to drive from community A to community B to enjoy a recreation opportunity as it would for people to drive from community B to community A. Therefore only distance determines the level of spillins (i.e. the spatial weight). If, on the other hand, travel was more difficult in one direction than another, the symmetric nature of the spatial weight matrix would not hold.

In dealing with transboundary pollution, the assumption of a symmetric spatial weight matrix is not always accurate. For example, meteorological and geographical considerations such as wind direction and mountain ranges will increase the probability of the pollutant traveling in certain directions. However some transboundary pollutants will have symmetric spatial weight matrices. Pollutants such as CFCs and CO_2 can be considered pure public goods. They are both nonrival and nonexcludable and have spatial weight matrices which consist entirely of ones.

More commonly, a transboundary pollutant will be an impure public good with both public and private benefits. For example, sulfur dioxide and nitrogen oxide emissions are nonexcludable but only partially nonrival and generate non-symmetric spatial weight matrices. In addition, these pollutants have different residence times in the atmosphere. Nitrogen oxides remain in the atmosphere longer than sulfur dioxide[4] so that the spatial weight matrix for nitrogen oxides is more evenly distributed than the matrix for sulfur dioxide. Residence times in the atmosphere are in fact, the main determinant of the degree of publicness of the pollutant. The longer an air pollutant remains in the atmosphere, the more public effects predominate over private ones.

While spatial weight matrices are often computed by using a distance formula, the matrices for a transboundary air pollutants are much more difficult to calculate. In the case of sulfur dioxide, and nitrogen oxides, monitoring stations and computer models are required to develop the spatial weights for each country. Fortunately, the spatial weight

---

[4] NO_x remains in the atmosphere from 2 to 8 days while sulfur emissions remain from .01 to 7 days (Alcamo and Runca, 1986).

matrix (sometimes referred to as a diffusion or transport matrix) for the European countries has already been calculated for these pollutants as part of the program of study began under LRTAP (Sandnes, 1993). The Meteorological Synthesizing Center-West (MSC-W) at the Norwegian Meteorological Institute produces yearly matrices based on reported emissions, collected depositions, and computer models.

This dissertation breaks new ground in the area of existing public goods literature in three ways. First, it uses an advanced spatial autoregressive model that can deal with both time-series and cross-section data. Second, it models transboundary air pollution as an impure public good and uses a spatial weight matrix to characterize fundamental differences between transboundary air pollutants. Third, the model is empirically tested using actual time-series cross-section data for 25 European countries regarding emissions reductions.

The work in the dissertation can be distinguished from several important papers that have recently dealt with the issues of transboundary air pollution and/or the spatial aspects of public goods. The paper by Mäler (1989) looked only at sulfur emissions and used a simulation analysis to find the Pareto-efficient (full-cooperation) outcome which was compared with: 1) the Nash equilibrium, 2) a full cooperative equilibrium with side payments, and 3) a Pareto dominating outcome without side payments. This dissertation examines both sulfur and NO_x emission reductions over the course of several years to see whether emission reductions were consistent with a Nash equilibrium based on independent adjustment.

The model used by Murdoch, Rahmatian, and Thayer (1993), was used to examine recreation demand expenditures by local governments using a median-voter model and a symmetric spatial weight matrix based on distance. In contrast, my dissertation uses an oligarchy choice model and a non-symmetric spatial weight matrix. Unlike the "snapshot in time" approaches used by Murdoch, Rahmatian, and Thayer (1993) and other empirical works dealing with public goods, the model used here allows year by year comparisons to be made using a single regression. In addition actual country data is used which gives the paper an empirical grounding distinguishing it from the theoretical papers of Barrett (1994), Carraro and Siniscalco (1993), and Heckathorn (1989) which examined the optimal provison of a generalized public good. Finally, the examination of how specific spatial weight matrices affect the payoffs of a game is a new contribution to the theory of public goods, although a general discussion of the problem can be found in Sandler and Sargent (1995).

In the next chapter I turn my attention to the formation of transnational treaties when the intentions of other nations are uncertain. I focus on the variety of outcomes that occur when nations are attempting to manage a transnational public good. The probability of cooperation is shown to depend upon the number of required members in the group, the pattern of payoffs, transactions costs, and the technology of public supply aggregation.

CHAPTER 3. MANAGEMENT OF TRANSNATIONAL COMMONS: COORDINATION, PUBLICNESS, AND TREATY FORMATION

Introduction

Although the diffusion of pollutants among neighboring states has been recognized for some time, recent exigencies (e.g., the appearance of a hole in the stratospheric ozone shield, the accumulation of atmospheric carbon and other greenhouse gases, and the raised acidity of soils and fresh-water bodies) have underscored the need to consider pollution of a regional and even global nature. Such pollution phenomena have transnational implications that may require coordination that transcends the nation-state.

Actions at the national level may ameliorate the problem, but they are anticipated to fall short of a social optimum, because nations are not expected to include the marginal impact of their behaviors on the residents of other nations. Transnational cooperation requires an enforceable agreement or treaty that restricts pollution beyond nationally imposed limits. Moreover, treaties must be individually rational so that each participant anticipates a net gain from the agreement (Barrett, 1991; 1992).

The institution of transnational treaties raises a host of issues. First, the formation of such treaties must be addressed, and this raises the question of the minimal-sized coalition needed for ratification (see Black, Levi, and de Meza; 1993). An increase in the number of ratifiers creates a trade-off between the efficiency gains from increased participation and the opportunity to free ride by the nonparticipants. Transaction costs may also rise as the size of the ratification group increases. Second, treaty adherence must be investigated, and this involves the notions of uncertainty and time-consistent behavior, in which short-run gains from defection may outweigh long-run losses from punishment once a treaty is signed and a contingency occurs.[1] Third, treaties may need to evolve over time as technology alters the configuration of net payoffs.

The focus here is on treaty formation *when efforts must be coordinated among a minimal-sized group so as to make cooperation worthwhile*. In particular, I stress the ability to achieve cooperation when the actions of others are uncertain. When a minimal-sized coalition is needed, and acting alone is more beneficial than cooperating when the minimal threshold is not attained or maintained, incentives exist for potential participants to act alone even though cooperation is the Pareto-optimal equilibrium. This incentive to defect gives rise to the uncertainty. Throughout, I ignore the existence of an enforcement mechanism, because there is no such mechanism for transnational treaties. Thus, nations cannot be certain that others will abide by a treaty, and must act based on their skepticism. A *coordination game* is shown to be appropriate for transnational commons problems that necessitate a minimal set of cooperators.[2] This is not to say that a coordination game is the essence of all transnational environmental problems. I assert, instead, that when minimal-sized coalitions are needed for effective cooperation, these problems may be best characterized as a coordination game. I investigate the diversity of public good

---

[1] For example, a nation may sign a treaty pledging never to negotiate with terrorists when hostages are taken, but may then decide to renege if a sufficiently valuable person is abducted, even though such behavior invites more hostage-taking.

[2] On coordination games, see Cooper et al. (1990), Farrell (1987), Runge (1984, 1990), and van Huyck, Battalio, and Beil (1990).

characteristics among alternative commons problems. Most analyses[3] lumped commons problems together as sharing the same public good characteristic so that a single prescription and model are intended to apply to a host of commons scenarios (Carraro and Siniscalco, 1993; Herber, 1991).

Coordination Games and Treaty Formation

For many transnational commons problems, a minimal degree of international coordination is required if an agreement to curb pollution is to have beneficial effects for the signers. This follows because, without this threshold of cooperation, nonparticipants can free ride on the restraint of the participants, thereby severely limiting or offsetting pollution cutbacks. Thus, in the case of stratospheric ozone depletion, the major producers[4] of chlorofluorocarbons (CFCs) must all be party to the treaty or else a nonratifier may expand its CFCs market share as the treaty goes into effect. This action of the nonratifier could give it sufficient gains to offset losses from its added pollution. Moreover, treaty members must be reasonably certain, as defined below, that ratifiers will adhere to their pledged actions.

To capture these features, I characterize some treaty formations as coordination games among two or more nations, in which potential ratifiers are uncertain about the actions of others. This paradigm permits me to focus on the influence of group size, the

---

[3] A notable exception is Chichilnisky and Heal (1993), which indicated the diverse public character of global commons problems.

[4] Most CFCs were produced by 16 firms located in the U.S., Europe, and Japan. Five of the 16, including Dupont with about 25 percent of the market share, are located in the U.S. (Morrisette et al. 1990, pp. 14-5).

degree of publicness, payoff configurations, and transaction costs on the ratification of treaties. A classic, but not the only, instance of a coordination game is the Stag-Hunt game presented in matrix a of Figure 3.1. Each player has two strategies: hunt stag or hunt hare, which I denote as C (cooperate) and D (defect), respectively. To bag a stag, both hunters must coordinate their actions to obtain payoffs of 2 for each player. If, however, only one player hunts stag while the other hunts hare, the stag hunter comes back empty-handed (i.e., a payoff of 0) and the hare hunter succeeds in snaring a hare worth 1. When both hunt hare, each receives 1 as a payoff. In matrix a, the rows indicate the two strategies of player 1, and the columns denote those of player 2. The first number in each cell is the payoff or net gain of player 1, while the second number is the net gain of player 2. For either player, there is no dominant strategy that gives higher payoffs no matter what the other player does, because a payoff of 2 exceeds a payoff of 1, while 0 does not exceed 1.

Even though coordination games do not contain dominant strategies, they possess multiple Nash equilibria in terms of pure and mixed strategies. A Nash equilibrium results when neither player would unilaterally want to change his/her strategic choice. As such, a Nash equilibrium represents the best (optimizing) response for a player, given his/her opponent's (opponents') best response(s). In matrix a, the cells marked with an asterisk are the two pure-strategy equilibria. When both hunt stag (hare), neither could gain from hunting hare (stag) alone, because 2 > 1 (1 > 0).

		Player 2		
		C	D	
Player 1	C	* 2, 2	0, 1	p
	D	1, 0	* 1, 1	1-p
		q	1-q	

Matrix a

		Player 2		
		C	D	
Player 1	C	U, U	B, A	p
	D	A, B	A, A	1-p
		q	1-q	

Matrix b

		Player 2		
		C	D	
Player 1	C	U, U	B, E	p
	D	E, B	A, A	1-p
		q	1-q	

Matrix c

		Player 2		
		C	D	
Player 1	C	U, U	0, A	p
	D	1, 0	1, A	1-p
		q	1-q	

Matrix d

		Player 2		
		C	D	
Player 1	C	U, S	0, 1	p
	D	1, 0	1, 1	1-p
		q	1-q	

Matrix e

		Player 2		
		C	D	
Player 1	C	U-T, U-T	B-T, A	p
	D	A, B-T	A, A	1-p
		q	1-q	

Matrix f

Figure 3.1. Coordination Games

A third Nash equilibrium involves mixed strategies in which each pure strategy is played in a probabilistic fashion. To find this mixed-strategy equilibrium, I determine the probability q of cooperation for player 2 that makes player 1 indifferent between strategy C and D. Similarly, the probability p of cooperation for player 1 is what makes player 2 indifferent between the two strategies. Once p and q are ascertained, equilibrium probabilities for defecting (i.e., hunting hare) equals 1 - q and 1 - p for players 2 and 1, respectively. The relevant probabilities for players 1 and 2 are indicated besides the respective row and column in matrix a. Solving for p and q, I get $p = q = 1/2$. If, therefore, player 1 is uncertain as to whether the other player will hunt stag, then player 1 should hunt stag provided that he/she expects the other player to hunt stag with probability greater than 1/2.

If, by analogy, two nations are contemplating a treaty to control pollution and both must act to realize any cooperative gains, then the Stag-Hunt game is appropriate. When nations are certain of the other nation's cooperative pledge, the (C, C) equilibrium would be focal, inasmuch as its payoffs dominate those of (D, D) (see Harsanyi and Selten, 1988, 80-1). If, however, nations are distrustful of one another, then a mixed strategy makes sense, in which each nation must anticipate the likelihood of cooperation on the part of the other nation. Distrust is relevant whenever cooperating alone has a lower payoff than defecting, because the player cannot be certain that the needed coordination will be forthcoming. In experimental research, van Huyck, Battalio, and Beil (1990) found that coordination failures in such games occurred frequently despite the focal nature of the coordination equilibrium. Moreover, the larger was the minimal size of the required coalition, the greater was the possibility of this coordination failure.

This analogy can be extended to a case of homogeneous players or nations that require, say, eight ratifiers to achieve gains from a cooperative pact or treaty. Suppose that eight cooperators would each receive 2, while any number less than eight gains nothing from cooperation. Further suppose that independent behavior gives a benefit of 1. This scenario generalizes the Stag-Hunt game to eight players. If players are uncertain about the actions of others, then each agent would cooperate provided they anticipated that all seven other players in aggregate would cooperate with probability greater than 1/2. When players' probabilities are independent, each player must then cooperate with probability greater than .9057 (the seventh root of .5) to make cooperation a desirable strategy. With a minimal-sized group as small as eight, each player must be viewed as quite likely to ratify and adhere to the cooperative agreement to make it worthwhile. Obviously, an increase in the minimal-sized groups of ratifiers cuts down on the likelihood of ratification, because each player must be more certain of the actions of others to ratify for it to be in the player's own interest to ratify.

In Table 3.1, I indicate the probability of ratification and adherence required of each player for alternative sized groups and overall adherence probabilities for the other n - 1 ratifiers. Consider a .5 overall probability of adherence. If 41 countries must cooperate for any to achieve gains, then each must be expected to cooperate with probability .9828 or greater to make ratification desirable. As shown, any increase in the

Table 3.1. Required Anticipated Probability of Treaty Adherence for Each Potential Participant When Agents are Homogeneous and a Minimal-Sized Coalition is Needed

	Minimal Required Probability of Adherence for Collective of Other Participants				
Number of Other Participants	.1	.3	.5	.7	.9
2	.3162	.5477	.7071	.8367	.9487
3	.4642	.6694	.7937	.8879	.9655
4	.5623	.7401	.8409	.9147	.9740
5	.6310	.7860	.8706	.9311	.9791
6	.6813	.8182	.8909	.9423	.9826
7	.7197	.8420	.9057	.9503	.9851
8	.7499	.8603	.9170	.9564	.9869
9	.7743	.8748	.9259	.9611	.9884
10	.7943	.8866	.9330	.9650	.9895
20	.8913	.9416	.9659	.9823	.9947
30	.9261	.9607	.9772	.9882	.9965
40	.9441	.9703	.9828	.9911	.9974
50	.9550	.9762	.9862	.9929	.9979
60	.9624	.9801	.9885	.9941	.9982
70	.9676	.9829	.9901	.9949	.9985
80	.9716	.9851	.9914	.9956	.9987
90	.9747	.9867	.9923	.9960	.9988
100	.9772	.9880	.9931	.9964	.9989
120	.9810	.9900	.9942	.9970	.9991
140	.9837	.9914	.9951	.9975	.9992
160	.9857	.9925	.9957	.9978	.9993
180	.9873	.9933	.9962	.9980	.9994

Note: The minimal-sized coalition is one greater than the number of other participants needed.

minimal-sized group raises the cooperation probability required to the potential participants. With sufficiently great adherence probabilities for the <u>other</u> participants, near certainty may be required for even small groups. Thus, each player must choose cooperation with probability greater than .9147 for a group of 5 to make cooperation desirable when an overall adherence probability of .7 is is required. I show below what determines the overall adherence probability for the collective of other participants. Table 3.1 highlights a number of important features of coordination games. First, even a modest sized group may experience coordination failure unless potential participants are reasonably certain that others will cooperate. This may not bode well for global treaties, unless very limited number of particpants are needed. Second, the probability of cooperation required of participants reaches near-certain levels rapidly and then increases slowly with additional group size requirements. For an adherence probability of .7, groups of 41 and 181 need individual probabilities of .9911 and .9980, respectively, to make cooperation desirable.

Thus far, my analysis paints a very pessimistic picture of coordination among a minimal-sized coalition. Several important caveats are in order. First, I emphasize that the analysis only applies to commons problems where a minimum coalition or threshold effort is needed before benefits can be gained.[5] If free riding can undo the cooperative gains that others provide, then this scenario is justified. Second, coordination probabilities

---

[5] Even if an agreement only becomes binding when the minimum coalition signs, uncertainty may arise owing to adherence problems. Nations may later renege on the treaty due to a short-term gain that might benefit only a subset of individuals.

may not be independent as assumed. If these probabilities are correlated, then the likelihood of cooperation would be greater than shown in Table 3.1. This correlation can be achieved through the leadership of a major country, whose actions induce others to act (Runge, 1993; 1994). Third, preplay communication can also increase the likelihood of coordination, but may not eliminate the uncertainty for some kinds of coordination games. Farrell (1987, 36-9), for example, has shown that preplay communication still leaves uncertainty for "Battle of the Sexes" coordination games. This analysis applies to some other kinds of coordination games. Given these caveats, my analysis must be viewed as providing a pessimistic index (Runge, 1993; 36). Much of the analysis here presents this pessimistic view, but the qualitative results would apply to a more optimistic correlated view.

In Figure 3.1, matrices b-e represent other cases of two-player coordination games for symmetric and asymmetric players. By examining these matrices, I am able to ascertain the determinants that influence the overall adherence probability. Matrix b is a symmetric version of the coordination game where $U > A > B > 0$, so that mutual cooperation yields greater payoffs than mutual defection. Furthermore, mutual defection is better than defecting alone. Given these payoffs, there is no dominant strategy, but there are three Nash equilibria -- (C, C), (D, D), and a mixed-strategy equilibrium. By equating player 1's expected payoff from strategy C (weighted by player 2's probabilities q and 1 - q) <u>to</u> player 1's expected payoff from strategy D (weighted by player 2's probabilities), I can solve for the Nash equilibrium level of q. A similar calculation can be executed using player 2's expected payoffs weighted with player 1's probabilities of p and 1 - p. For the symmetric matrix, a mixed-strategy equilibrium results when

$$p = q = (A - B) / (U - B). \tag{3.1}$$

When p and q exceed this value, cooperation is the best strategic choice.[6] The ratio in equation (3.1) represents the coordination probability that each player requires of the other player in order to want to cooperate. A smaller probability favors successful coordination, since a player needs to be less certain of the other player's intention to cooperate in order to reciprocate. Equation (3.1), shows that large cooperative gains (U) and small noncooperative gains (A) promote the cooperative equilibrium by reducing the required adherence probability. An increase in the payoff (B) associated with cooperating alone also promotes cooperation, since I have

$$dq / dB = dp / dB = (A - U) / (U - B)^2 < 0. \tag{3.2}$$

If cooperation has private payoffs even when overall coordination is not achieved, then a player needs to be less certain about his/her counterpart's intentions when deciding to act in a cooperative fashion. This result proves useful when evaluating the likelihood of treaty formation for various transnational commons dilemma.

Matrix b can be generalized to a symmetric game with n homogeneous players. Such a generalization would imply that, at least, n players must cooperate if each participant is to receive a payoff of U. When less than n players coordinate, each receives

---

[6] For 2-player games, a related notion for choosing an equilibrium is that of risk dominance, introduced by Harsanyi and Selten (1988, 82-90). For matrix b, equilibrium (C, C) risk dominates (D, D) if $(U - A) / (A - B) > (A - B) / U - A)$ or $(U - A)(U - A) > (A - B)(A - B)$, so that the product of the gains from cooperating exceeds the product of the gains from mutual defection when the other player defects.

B for cooperating and A for not cooperating. If players are uncertain about the cooperation intentions of others, then cooperation is a desired strategy provided that a player believes that the n - 1 required additional cooperators will follow through with probability greater than q. This, in turn, implies that for the pessimistic case each individual must be expected to cooperate by at least the n - 1st root of q, which for even modest group sizes may require near certainty as shown in Table 3.1.

In Figure 3.1, matrix c depicts another two-player symmetric coordination game, but where payoffs for defecting (A or E) depends on whether or not the other player defects. When the intentions of others are unknown, the mixed-strategy equilibrium is

$$p = q = (A - B) / [U - B + (A - E)], \tag{3.3}$$

which differs from equation (3.1) by the additive factor (A - E) in the denominator. At least two cases can be distinguished: $U > A > E > B$ and $U > E > A > B$. In the first, cooperation is promoted as compared with matrix b, while, in the second, cooperation is not fostered. This follows because unilateral defection is more (less) profitable in case 2 (case 1) than in matrix b. Treaty sanctions are meant to foster the payoff configuration of case 1.

Matrices d and e are used to indicate two asymmetric coordination games. In matrix d, player 2 gains relative to player 1 when defecting for $A > 1$. That is, player 2 is more skilled in going it alone (hunting hare) than player 1. The mixed-strategy equilibrium requires

$$p = A / U > 1 / U = q, \tag{3.4}$$

so that player 2 needs greater assurance than player 1 that his/her counterpart will follow through with cooperation. Heterogeneity involving defection payoffs is not anticipated to support coordination when players' intentions are uncertain (also see Runge 1984).

I next consider heterogeneity in terms of coordination gains. For $S > U$ in matrix e, player 2 gains relative to player 1 when coordination is achieved As a consequence, player 2 requires less certainty that player 1 will cooperate, since

$$p = 1 / S < 1 / U = q. \qquad (3.5)$$

Matrices d and e have n-player analogues in which the overall adherence requirement equals the product of the individual probabilities associated with cooperation. Thus, the overall adherence probability for the rest of the collective is conditional on all $n - 1$ players, whose probabilities can differ, cooperating. As before, an increase in group size, ceteris paribus, reduces the likelihood of coordination.

Thus far, I have considered discrete choices in which each player can cooperate or not. The analysis could be extended to continuous choices where each of n players must exert more than a minimal effort of x for the coordination to succeed. If each individual's effort is independent and identically distributed with a common cumulative distribution function (cdf) equal to $F(x_j)$, then the cdf for the minimum is

$$F_{min}(x) = 1 - [1 - F(x_j)]^n. \qquad (3.6)$$

Even a small probability that the minimum might not be met will drive $F_{min}(x)$ to 1 and make cooperation unlikely. Of course, the standard caveats apply.

Transaction Costs

When nations are interested in cooperation, transaction costs are expended during negotiations and throughout the duration of an agreement. For coordination games, the likelihood of a cooperative agreement can depend on the amount of transaction costs and the manner by which it is incurred. To demonstrate, I extend my analysis of coordination games to various transaction costs scenarios. As before, I present a pessimistic viewpoint by assuming probability independence and the absence of preplay communication.

The simplest two-player case corresponds to matrix f in Figure 3.1, where transaction costs of T are incurred by any player who cooperates. In this baseline case, only the cooperators pay the transaction costs per person, which are the same whether coordination is achieved or not. Each player receives U - T when coordination is achieved; B - T when cooperation is not reciprocated; and A when acting independently. If these transaction costs are less than U - A (i.e., the gains from cooperation), then the coordination equilibrium continues to payoff dominate the noncoordination equilibrium. When players are uncertain about the other player's intention, the cooperation equilibrium is the desired outcome when

$$p = q > (A - B + T) / (U - B). \qquad (3.7)$$

Compared with the adherence probabilities in equation (3.1), the new probabilities are now higher, thus cutting down on the likelihood that coordination will succeed as compared with the absence of transaction costs. Quite simply, transaction costs limit cooperative gains and this, in turn, makes players want greater certainty that others will carry through with cooperation.[7]

I next distinguish between transaction costs, T, when coordination is achieved, and those, $\bar{T}$, when coordination is not achieved, where $T > \bar{T}$. Full coordination is now anticipated to be more costly than partial cooperation. For matrix f, this alteration means that B - T is replaced with $B - \bar{T}$ in the off-diagonal cells. The mixed-strategy equilibrium now requires

$$p = q = (A - B + \bar{T}) / (U - T + \bar{T} - B), \tag{3.8}$$

which is less than the probability in equation (3.7), since the same positive factor, $T - \bar{T}$ has been subtracted from the numerator and denominator of equation (3.7). As compared to the first instance of transaction costs, each player is now willing to cooperate with less certainty that the other player will also cooperate. This follows because the losses from misjudging the other player's intentions to cooperate [i.e., $U - (B - \bar{T})$] are now smaller than the first case. An apt analogy for treaties and agreements concerns refundable transaction costs or payments, since partial refundability essentially acts to make $\bar{T}$ less than T, and thereby fosters the likelihood of an agreement. A useful institutional principle to remember is that refundability in the absence of a coordinated equilibrium is inducive to an agreement.

---

[7] This case also reduces the risk dominance of (C,C) over (D,D), since risk dominance now requires $(U - A - T)(U - A - T) > (A - B + T)(A - B + T)$ which is more stringent and less apt to be satisfied than the condition in footnote 6.

A final two-player case allows transaction costs asymmetry so that those of, say, player 1 exceed those of player 2. Player 1 would then require a greater likelihood that player 2 will cooperate so that q > p.

For a minimal-sized coalition of n players, a number of transaction costs scenarios are relevant. Suppose that the payoffs in matrix f apply to the n-player case, so that coordination gives each player U - T; coordination failure gives B - T to the cooperators and A to the others; and uniform defection gives A to each player. The likelihood of coordination then falls with n and is less than in the absence of transaction costs. Another relevant case has transaction costs, T, rising as the minimal number, n, of cooperators increases, while coordination benefits are independent of n. An increase in n again reduces the likelihood of coordination, but at a faster rate than the previous case, because n affects the individual adherence probabilities by raising q and the number of roots of this probability that must be found. Another case involves a proportional increase in U and T equal to n so that U - T is unchanged but B - T falls. An increase in n again works against the achievement of coordination by raising q and the number of required roots of this probability. Even if net benefits from coordination are favorably influenced by group size in proportion to n, agreements are less likely, because n has an exponential influence through root taking on individual cooperation requirements. For most reasonable scenarios, transaction costs enhance the negative impact on treaty formation associated with an increase in the minimal coalition.

The Technology of Public Supply Aggregation

Another important, but overlooked, factor in the study of coordination games and treaty formation is publicness attributes of the coordination problem under consideration. In the environmental literature, pollutants from diverse sources are often modeled with a summation technology (see, e.g., Barrett, 1991, 1992; Eyckmans, Proost, and Schokkaert, 1993; Herber, 1991). In other instances, cooperative solutions are analyzed for a generic problem without distinguishing among diverse pollution scenarios (e.g. Black, Levi, and de Meza, 1993; Carraro and Siniscalco, 1993). I intend to show that the technology of public supply aggregation,[8] which indicates how individual pollution activities add to the total pollutants experienced, has important implications for the achievement of a coordination equilibrium.

For simplicity, I distinguish four such technologies: (1) summation, (2) weighted summation, (3) weakest link, and (4) joint products. Let g denote the pollution emissions of nation (player) i, and let G represent the aggregate emissions of all nations (players). If, instead, the cleanup or protection of a commons is investigated, then g_i indicates individual protective actions and G depicts aggregate protection. For a summation technology,

$$G = \sum_{i=1}^{n} g_i \tag{3.9}$$

---

[8] Hirshleifer (1983) used the alternative term, social composition function, to denote this technology. Also see Sandler (1992, chapters 2-3).

so that each contributor's impact on aggregate G is identical at the margin. This technology characterizes pure public good subscription models as well as analyses of the pure commons. Global examples include ozone shield depletion and global warming.

Marginal impacts differ among players according to the weights, w_i, in the weighted-sum technology:

$$G = \sum_{i=1}^{n} w_i g_i \tag{3.10}$$

which applies to impure public goods where the location of the source of the pollutant makes a difference owing to wind direction, barriers, or other considerations. Acid rain is best characterized by such a technology.

A third technology is weakest link in which

$$G = \min\{g_1, g_2, \ldots, g_n\}, \tag{3.11}$$

where the smallest provision effort level of the group determines the collective provision (Hirshleifer 1983). Prophylactic measures taken to forestall the spread of a disease or a pollutant abide by this technology.

A fourth technology is that of joint products where an activity gives rise to multiple outputs that may vary in their degree of publicness. For example, a pollutant may have both a country-specific localized impact on the emitter and a global impact or public effect on all nations.

Perhaps the best means for demonstrating the potential impact that these four technologies can have on coordination equilibria is through a series of numerical examples for 2-player bimatrix games. In Figure 3.2, the top two matrices correspond to a weakest-link and joint product technology. As before, each player has two strategies: cooperate (C) or defect (D). In the weakest-link example, each player can contribute 1 or 0 units to a collective activity. Each player must contribute a unit at a cost of 3 before per-player gross benefits of 5 can be received. Thus, a nonlinear threshold effect is assumed. When both players contribute, each receives 2 in net benefits (5 - 3) from coordinating efforts. If neither contributes, then each gets 0, while a single contributor gets -3, since the smallest contribution is 0 units and costs for the single unit must be paid. With uncertain intentions, the mixed-strategy equilibrium occurs when $p = q = 3/5$. Weakest-link technologies are invariably associated with coordination game structures. At the coordination equilibrium, players match one another's contributions, because there are no gains, just costs, from exceeding the minimal contribution. If the players can contribute additional units of the collective activity, then the pure-strategy Nash equilibria occur along the primary diagonal where matching takes place. The n-person analogue for the weakest-link technology also implies matching behavior.

Joint products may also give rise to coordination games as illustrated by matrix b in Figure 3.2. This two-player game's payoffs are based on each unit of an individual contribution yielding an individual-specific benefit of 5 and a public benefit of 2. The public benefit is experienced only if a minimal contribution of 2 units is achieved. The

		Player 2	
		C	D
Player 1	C	2, 2	-3, 0
	D	0, -3	0, 0

a. Weakest Link

		Player 2	
		C	D
Player 1	C	3, 3	-1, 0
	D	0, -1	0, 0

b. Joint Product

		Player 2	
		C	Nash
Player 1	C	12, 12	0, 3
	Nash	3, 0	3, 3

c. Summation

		Player 2	
		C	Nash
Player 1	C	4, 4	-2, 1
	Nash	1, -2	1, 1

d. Weighted Sum

Figure 3.2. Numerical Examples Of Alternative Technologies Of Public Supply Aggregation

individual-specific benefit follows whether or not the minimal contribution is met. In this example, each unit costs 6. When coordination occurs and each player provides a unit, the payoffs to the players are 3 apiece, which equals the sum of the private benefit of 5 and the public benefit of 4 (= 2 times the number of units provided) minus costs of 6. If only one player contributes, then the contributor receives -1 (= 5 - 6) and the other player receives 0. The absence of any contributions gives nothing to each player. When the joint product technology is associated with a coordination game, the private benefits act to raise the gains from unilateral cooperation. As shown earlier, this serves to foster cooperation, since smaller probabilities of cooperation on the behalf of the other player are required in order to make contributing desirable. Paradoxically, large private benefits <u>relative</u> to public benefits foster cooperation, but the net gains from such cooperation can be relatively small owing to the extent of private benefits.[9] Nevertheless, joint products can be supportive of treaties and coordinated actions.

The bottom two matrices involve summation and weighted sum technologies where a minimal degree of coordination is mandated before the summed benefits from spillins (i.e., gains derived from the actions of others), beyond the Nash equilibrium, are experienced. If, however, a minimal degree of coordination is not required, then summation and weighted sum technologies imply a Prisoners' Dilemma game with a dominant strategy to defect (Sandler 1992, 39-41). Hence, minimal coordination is a

---

[9] This result has the same character as that of Barrett (1991, 1992) who found that treaties are more likely in those cases where the relative gain is small.

crucial feature here. Each player has two strategies: (1) to provide the Nash contribution of one unit, or (2) to provide the cooperative (C) contribution of four units. Each unit costs 5. For the summation matrix, each unit contributed gives the contributor 4. Spillin benefits of 4 are experienced from only the first unit provided by others until at least eight units in total are provided. Once this threshold is achieved, every unit of provision by others gives 4 in spillin benefits. If, therefore, both players provide four units, then each receives net benefits of 12 [= (8 × 4) - (5 × 4)]. When one player provides four units and the other contributes one unit, the four-unit contributor receives 0 (= 4 × 4 + 4 - 4 × 5), since spillin benefits are derived from only the first unit contributed by the other player, and the one-unit contributor gets 3 (= 4 + 4 - 5). If both contribute one unit, then each receives 3 in net benefits. For uncertain intentions, mutual cooperation is desirable if p and q exceed 1/4.

This example forms an interesting contrast with a weighted-sum technology where the underlying payoffs are the same except that spillins, when they occur, only give 2 per unit in benefits, implying that one's own actions are more productive than those of others. The payoffs for matrix d are computed as before and again result in a coordination game. If intentions are unknown, then p and q must now exceed 1/2 if coordination is best. When compared to the summation case, the weighted-sum technology reduces the net gains from cooperation, so that a coordinated equilibrium is more difficult to achieve. The smaller is the weight given to spillins, the less likely is cooperation. Once again, I see that the technology of public supply aggregation can impact the likelihood of cooperation.

The Relationship Between Spatial Weights and Public Supply Technologies

If a transboundary pollutant is an impure public bad, the decision to reduce the pollutant will result in some private benefits (cleaner air or less acid rain) whether or not coordination is achieved with other nations. All other things equal, the cooperative solution comes closest to the individual solution when the transboundary air pollutant is closest to a private good. The technology of public supply is one determinant of the level of private benefits. A weighted sum technology has the effect of making nations with the greater weights (greater private benefits) more likely to cooperate, emissions of sulfur and nitrogen abide by a weighted sum technology. Each nation gains private benefits from reducing pollution, but in addition there are public benefits to the other nearby nations.

By examining various spatial weight matrices, it is possible to see how different public supply technologies can be represented. For simplicity, assume that there are only two nations--nation A and nation B--and that emissions from one nation are either deposited in the country of origin or in the other country (i.e. no pollution lands outside of nation A or B). In this case a two by two spatial weight matrix is required, with the emitters represented by columns and the receivers represented by rows. Figure 3.3 contains eight spatial weight matrices representing four types of public supply technologies. The first matrix in each row records depositions in terms of the quantity of pollutant deposited, while the second matrix represents depositions as a percentage of emissions. In each of the four cases, nation A emits ten units of pollution, while nation B emits five units of pollution.

Emitter

$$\text{Receiver}\quad \begin{array}{c|cc|} & A & B \\ A & 10 & 0 \\ B & 0 & 5 \end{array}$$

a. Private Good
(absolute value)

Emitter

$$\text{Receiver}\quad \begin{array}{c|cc|} & A & B \\ A & 1 & 0 \\ B & 0 & 1 \end{array}$$

b. Private Good
(fractional value)

Emitter

$$\text{Receiver}\quad \begin{array}{c|cc|} & A & B \\ A & 10 & 5 \\ B & 10 & 5 \end{array}$$

c. Pure Public Good
(absolute value)

Emitter

$$\text{Receiver}\quad \begin{array}{c|cc|} & A & B \\ A & 1 & 1 \\ B & 1 & 1 \end{array}$$

d. Pure Public Good
(fractional value)

Emitter

$$\text{Receiver}\quad \begin{array}{c|cc|} & A & B \\ A & 8 & 1 \\ B & 2 & 4 \end{array}$$

e. Impure Public Good
with symmetry
(absolute value)

Emitter

$$\text{Receiver}\quad \begin{array}{c|cc|} & A & B \\ A & 0.8 & 0.2 \\ B & 0.2 & 0.8 \end{array}$$

f. Impure Public Good
with symmetry
(fractional value)

Emitter

$$\text{Receiver}\quad \begin{array}{c|cc|} & A & B \\ A & 6 & 0 \\ B & 4 & 5 \end{array}$$

g. Impure Public Good
with non-symmetry
(absolute value)

Emitter

$$\text{Receiver}\quad \begin{array}{c|cc|} & A & B \\ A & 0.6 & 0.0 \\ B & 0.4 & 1.0 \end{array}$$

h. Impure Public Good
with non-symmetry
(fractional value)

Figure 3.3. Spatial Weight Matrices

In the first case (matrices a and b) pollution is a private bad (it is both rival and excludable) and so does not classify as a transboundary pollutant. The ten units emitted by nation A affect only nation A. Therefore, a 10 and a 0 are the values for the first column. Likewise the five units emitted by B affect only B. Since no pollution from B falls on A, a 0 is the first element of the second column. And because all five units of pollution from B are deposited on its own soil, a 5 is the second element of the second column. Notice that the sum of the first column is ten and the sum of the second column is five, corresponding to the emissions coming from each country.

In matrix b the depositions are represented as a percentage of emissions. Therefore since 100% of A's emissions are deposited on A, and 0% are deposited on B, the first column values are 1 and 0. The same reasoning applies to the elements of column B giving a 0 and 1 respectively. In other words, the spatial weight matrix, for a private good, expressed in percentage terms, has 1's along the diagonal and 0's for the off-diagonal elements. Note that the sum of the columns adds up to 100%

In the case of a pollutant that is a private bad, a nation that equates the marginal private benefit of reducing pollution with the marginal private cost will achieve the social optimum since the marginal private benefits of pollution reduction are identical to the marginal social benefits. Each nation will select the optimal amount of pollution emissions, since there are no public effects to consider. An example of a pollutant that is a pure private bad would be nuclear waste (assuming it is not dumped at sea or transported secretly to another country).

An identical spatial weight matrix is also possible for the case of an impure public bad that is rival but non-excludable, but only if the pollutant stays confined within a country's borders. In both cases, the matrix is symmetric with all off diagonal elements equal to zero and all diagonal elements equal to one.

In the case of a pure public bad (matrices c and d) which has the properties of both nonrivalry and nonexcludability, the spatial weight matrices look quite different. Nation A emits ten units of pollution affecting both itself and nation B, and nation B emits five units which also affects nation A and itself. Both nations therefore have to cope with 15 (10+5) units of damage from the pollution. Notice that the column sums of matrix c are greater than the emission levels of each country. Converting the "depositions" into a percentage of the total emissions gives matrix d. All elements of this matrix are equal to one (i.e. 100%). Examples of pollutants with pure public bad properties include CFCs and carbon dioxide. Both are gases that easily dissipate in the atmosphere and cause world-wide rather than localized problems.

In the case of a pollutant that is an impure public bad (i.e. one that is rival and non-excludable), spatial weight matrices similar to e and f or g and h result. In the first case, the dispersion of the pollutant is symmetric (but this symmetry is only visible in matrix f). Eight of the ten units (80%) emitted by nation A fall in nation A, while the two remaining units (20%) fall in nation B. Of B's five units of pollution, one unit lands on A (20% of B's total emissions) and four units land on B (80%). Notice that matrix f, the spatial weight matrix represented in percentage terms, is symmetric with 80% along the diagonals and 20% in the off diagonals.

If one nation is downwind of another, a transboundary pollutant with the properties of an impure public bad will generate a non-symmetric spatial weight matrix (in percentage terms). This case is illustrated in matrices g and h. Here six units (60%) of nation A's emissions falls on itself while four units (40%) falls on B. However all five units (100%) of B's emissions lands on its own soil. Notice that in both cases of an impure public bad, the column sums of matrices e and g are equal to the total emissions and that the column sums of f and h add up to 100%. Sulfur dioxide and nitrogen oxides are transboundary pollutants that fall into the category of impure public goods.

The spatial weight matrices (in percentage terms) for sulfur dioxide and nitrogen oxides both show a strong diagonal component indicating that much of a nation's pollution lands on its own soil. However, much less of a country's emissions of nitrogen oxides lands on its own soil than does its sulfur emissions. Furthermore, nitrogen oxides generally diffuse faster than sulfur emissions so that countries receive a smaller percentage of NO_x depositions from their neighbors compared with sulfur depositions.

Since other nations will benefit when a nation reduces its own emissions of a transboundary air pollutant, the marginal social benefit of reducing air pollution is greater than the marginal private cost of controlling it, and therefore it is expected that the optimal amount of pollution (or pollution control) will not be chosen. That is, the cooperative solution which equates marginal social benefit with marginal social cost will not occur.

Instead nations are expected to equate their marginal private cost of reducing pollution to their marginal private benefits. The result is an underprovision of the public good (emission reductions) and an overprovision of the public bad (air pollution).

Spatial Weights, Payoffs, and Dominant Strategies

It is possible to represent the choice of pollution control as a game theory problem. Suppose there are two nations, again I will use A and B, that can choose to cooperate or defect. By cooperating, a nation chooses its level of emission reductions by equating its marginal costs to both its own marginal benefits *and* the marginal benefits that other nations derive from its emission reductions. A nation defects when it chooses the level of reductions based only on the costs and benefits to itself. It should be emphasized that defection does NOT mean that a nation fails to limit its pollution but rather that it only limits pollution up to the point where its own marginal benefits are equal to its own marginal costs.

In some cases, if the transboundary air pollutant is an impure public good, the problem of whether to cooperate or defect can be represented as a Prisoner's Dilemma, such as that of matrix a in Figure 3.4. Suppose that both nations are identical and the spatial matrix (in percentage terms) is symmetric with all elements equal to 50%. Furthermore, suppose that when each nation defects it chooses to reduce its emissions by one unit at a private cost of five but which gives ten in total world benefits. Each nation then gets a private benefit of five (50% of ten) and gives five in spillover benefits to the

		Nation B	
		C	D
Nation A	C	7, 7	3, 9
	D	9, 3	* 5, 5

a. Prisoner's Dilemma

		Nation B	
		C	D
Nation A	C	* 7, 7	5.4, 6.6
	D	6.6, 5.4	5, 5

b. Fully Privileged

Figure 3.4. More Coordination Games

other nation. If both nations choose to defect, then the payoff for each nation is five (five in private benefits minus five in costs plus five in spillover benefits from the other nation).

Next, suppose that when the cooperative solution is calculated, two units of emission reductions are chosen. This time the private cost to reduce emissions by two units is assumed to be 11, reflecting an increasing marginal cost, and total world benefits provided are 18, reflecting decreasing marginal benefits. If both nations choose to cooperate then the payoff to both nations is seven. Each nation gets nine in private benefits (50% of 18) at a cost of eleven plus nine in spillover benefits from the other nation.

Finally, suppose that nation A chooses to cooperate and elects to reduce its emissions by two units while nation B chooses to defect and reduce its emissions by one unit. In this case, the payoff for A is 3, since it receives nine in private benefits (50% of

18) minus a private cost of 11 plus spillover benefits of five (50% of 10) from nation B's one unit of emission reductions. The payoff for nation B is 9, since it receives five in private benefits (50% of 10) at a private cost of 5 plus spillover benefits of nine (50% of 18) from nation A's two units of emission reductions.[11] The reverse holds if A defects and B cooperates; the result is a payoff of nine for A and three for B.

Since there is no enforcement mechanism to insure that nations carry out their agreements, this situation corresponds to that of transboundary air pollution, where no world government is able to enforce international treaties. In addition, nations are expected to make their choices simultaneously and without communicating with other nations. Therefore a nation can assume that its decision about whether to cooperate or defect will have no influence on the decision of another nation (i.e. each nation has a zero-conjecture reaction function).

If both countries cooperate by selecting the globally optimal level of pollution, then they are better off (with payoffs of seven for each) than if they both decide to act selfishly (in which case they each get five). However, both countries have strong incentives to defect. If A defects while B cooperates, A is much better off than if it had cooperated, and the same holds true for B. The result is that the dominant strategy for both nations is to defect. There are, of course, a.large number of alternative factors that influence the

---

[11] Notice that diminishing marginal benefits occur for both the cooperator and defector in this case as well. When both nations cooperate each unit of emission reductions is worth nine (18 × 2 in world benefits divided by 4 units of total emission reductions). When one nation cooperates and one defects each unit of emission reductions is worth 9.333 ((18 + 10) / 3). And if both nations cooperate, each unit of emission reductions is worth ten (10 × 2 / 2). Because each element of the spatial weight matrix is 0.5, each nation shares the world benefits from emission reductions equally, whether this is four (full cooperation), three (one cooperates and one defects) or two (full defection).

payoff structure and hence the outcome of international treaty formation, among these are: the size of the group, the public supply technology, and transactions costs. Each of these will be explored in the dissertation.

In the above case, the provision of the public good abides by a Nash equilibrium and both nations choose to defect.[12] Non-Nash equilibria, when players consider how their choices will affect the other player's choices, are also possible, but these are much more complicated and involve non-zero conjectures about the reactions of others (Cornes and Sandler, 1984b, 1996).

While defection is the individually rational outcome of playing the Prisoner's Dilemma a finite number of times, Barrett (1991) has suggested that if the Prisoner's Dilemma is played repeatedly (a supergame), cooperation may develop because defection can be punished by retaliation in the next and subsequent plays of the game (assuming that neither player knows when the game will end). Barrett believes that it is crucial that international environmental agreements must be self-enforcing.

When a minimal amount of cooperation is required to achieve a positive payoff or, in the following case, where there is a change in the spatial weight matrix, the dominant strategy may no longer be that of defection. Let us keep the same example as in matrix a of Figure 3.4 but change the spatial weights. Suppose that 80% of a country's emissions land on itself with the other 20% landing on its neighbor.

---

[12] A Nash equilibrium occurs when, given the other nation's best choice, neither nation has any incentive to change its strategy unilaterally.

In a fully privileged game, the payoffs for full cooperation and full defection do not change but the payoffs for one nation defecting and the other nation cooperating do change (see matrix b in Figure 3.4). In the case of full cooperation, each nation receives 14.4 (18 × 0.8) in private benefits at a cost of 11 + spillover benefits of 3.6. (18 × 0.2), for a total of 7 each. For full defection, each nation receives 8 (10 × 0.8) in private benefits at a cost of 5 and a spillover benefit of 2 (10 × 0.2), giving a total payoff of 5 for each. Finally in the case where one nation cooperates and the other defects, the defector gets 6.6 (eight in private benefits (80% of 10) at a cost of five plus spillover benefits of 3.6 (20% of 18) from the two units of emission reductions from the cooperator). The cooperator gets 5.4 (a private benefit of 14.4 (80% of 18) minus a private cost of 11 plus spillover benefits of two (20% of 10) from the one unit of emission reductions of the defector)[13]. Notice that the payoff for the defector in this case is less than the payoff for full cooperation.

Matrix b thus has a single dominant strategy (C, C) which is also a Nash equilibrium. Rational players will always choose the cooperative strategy and will never deviate from it. Even if one or both players deviate from the cooperative strategy, the structure of the payoffs will lead them back to cooperating.

---

[13] Again, this simplified method implicitly takes into account the decreasing marginal benefits of emission reductions. The cooperator gets benefits from 1.8 units of emission reductions (2 × 0.8 + 1 × 0.2) and the defector gets benefits from 1.2 units of emission reductions (1 × 0.8 + 2 × 0.2). 80% of the cooperator's (defector's) benefit is based on the full cooperation (defection) benefits--so the actual marginal benefit is underestimated (overestimated)-- while 20% is based on full defection (cooperation)--so the actual marginal benefit is an overestimate (underestimate). Thus, it turns out that the correct result is achieved, i.e. the marginal benefit of emission reductions is lower for the cooperator than for the defector but not as low as the marginal benefit when both countries cooperate.

Likewise, if a treaty can be designed so that the costs of pulling out exceed the benefits gained, the result is also an assurance game and the treaty is self-enforcing. However, a fully privileged game would require no treaty at all since once the payoff matrix is known, players will automatically choose the cooperative strategy and do not need any assurance about the actions of the other players.

Nevertheless, most transboundary pollution problems involving impure public goods will be more likely to result in payoff matrices that resemble matrix a rather than matrix b. If this were not the case, then there would not be so much debate over transboundary pollution control treaties--either there would be no need for treaties, or the treaties would be something of a formality and signed with little argument.

Applications to the Transnational Commons

Stratospheric Ozone Depletion

After considerable scientific debate and investigation, a consensus has formed that CFCs emissions produce a chemical reaction in the stratosphere that thins the ozone shield that protects all living organisms from harmful ultraviolet radiation (Morrisette et al., 1990). In 1985, the British Antarctic Survey presented evidence that a disturbing 40 percent drop (from 1964 levels) in the springtime atmospheric levels of ozone took place over Halley Bay, Antarctica, during the 1977-1984 period. Ozone depletion is nonrival because one nation's increased exposure to enhanced ultraviolet radiation does not lessen the risks to any other nation. Even though thinning initially takes place over the polar regions during the winter, the reduced density of stratospheric ozone is more or less evenly shared worldwide as mixing takes place in the upper atmosphere. Since nations cannot escape the increased ultraviolet exposure, the detrimental effects of ozone thinning are nonexcludable on a global scale. The ozone shield is a global commons and its depletion has the properties of a global pure public bad. Each nation's release of CFCs adds to the depletion in an additive manner with identical marginal impacts, so that a summation technology is relevant.

Just prior to the discovery of the Antarctic ozone hole, nations negotiated the Convention for the Protection of the Ozone Layer[14] in Vienna on 22 March 1985. This precursor to the Montreal Protocol mandated scientific evaluation of the ozone shield and its possible thinning from CFCs. The Vienna Convention was a symbolic breakthrough that helped pave the way to the subsequent Montreal Protocol of 16 September 1987 that actually established limits for the emission of CFCs and halons (see Murdoch and Sandler, 1997b and the United Nations Environment Programme (UNEP) 1991 on these limits). This protocol entered into force on 1 January 1989 following the required signatures of eleven or more ratifiers, a number arbitrarily mandated by the treaty.[15] Initial ratifiers included Canada, Denmark, Egypt, Finland, France, West Germany, Ireland, Italy, Japan, Malta, Mexico, the Netherlands, New Zealand, Norway, Spain, Sweden, the U.K., the

---

[14] See United Nations Environment Progamme (1991) for the text of the Vienna Convention and other multilateral treaties discussed in this paper.

[15] This number did not follow from game-theoretic or other considerations and is not viewed as a minimal-sized coalition.

U.S., and the U.S.S.R. Many other nations signed subsequently including Australia, China, East Germany, and South Africa.

But why did nations accomplish a coordinated equilibrium in the case of ozone depletion even though a summation technology is present? How were the payoffs conducive to this treaty? To address these questions, I first examine CFCs emission patterns as indicated in the left-hand half of Table 3.2, where the twelve largest CFCs emitters in 1989 are indicated. Emitters' rank, emission levels in thousands of metric tons, and percent of world total are given. The top three emitters account for half of the world's emissions, while the top twelve account for just over 78 percent. Thus, the minimal-sized group of ratifiers can be quite small. From my analysis of coordination games, I know that a small required number of ratifiers is conducive to treaty formation.[16] But eleven may still be restrictive unless the adherence probability for the rest of the group is correlated or very small, and this requires, in part, large payoffs from coordination. Correlated probabilities were probably achieved through the leadership actions of the U.S., whose net benefits from curbing CFCs use were large. Significant payoffs from multilateral actions have, indeed, been documented for the largest CFCs polluters by the U.S. Environmental Protection Agency (EPA). The EPA (1987a, 1987b) estimated that the implementation of the Montreal Protocol could save the U.S. $6.4 trillion by 2075 in reduced costs associated with skin cancers. The long-run costs from curbing CFCs uses, as mandated by the 1987 protocol, was estimated by the EPA to be between $20 and $40

---

[16] See Poterba (1993) on other factors that may have led to the signing of the Montreal Protocol.

Table 3.2. **Major Polluters Of CFCs And Industrial-Based CO_2: 1989**

CFCs[a]				Industrial-Based CO_2[b]			
Country	Rank	CFC Emissions (000 Metric Tons)	Percent of World Total	Country	Rank	CO_2 Emissions (000 Metric Tons)	Percent of World Total
U.S.	1	130	22.4	U.S.	1	4,869,005	22.3
Japan	2	95	16.4	U.S.S.R.	2	3,804,001	17.4
U.S.S.R.	3	67	11.6	China	3	2,388,613	10.9
Germany[c]	4	34	5.7	Japan	4	1,040,554	4.8
U.K.	5	25	4.3	India	5	651,936	3.0
Italy	6	25	4.3	W. Germany	6	641,398	2.9
France	7	24	4.1	U.K.	7	568,451	2.6
Spain	8	17	2.9	Canada	8	455,530	2.1
China	9	12	2.1	Poland	9	440,929	2.0
Canada	10	11	1.9	Italy	10	389,747	1.8
Australia	11	8	1.4	France	11	357,163	1.6
S. Africa	12	7	1.2	Mexico	12	319,702	1.5
Total		455	78.4	Total		15,927,029	72.9
World		580	100.0	World		21,863,088	100.0

[a] *Source*: World Resources Institute (1992, Table 24.2, pp. 348-49).
[b] *Source*: World Resources Institute (1992, Table 24.1, pp. 346-47).
[c] Includes West and East Germany.

billion throughout the 1989-2075 period. Expected payoffs from national coordination efforts were bolstered by scientific certainty, the availability of CFCs substitutes, and the concern expressed by many opinion leaders and the public in some of the major emitting nations.

Treaty negotiations limited transaction costs by mandating contributions to a multilateral fund only after ratification.[17] This negotiation tactic was also supportive of ratification. A comparison of the initial ratifiers and the major emitters indicates that most of these emitters were on board at the outset of the treaty or came on board shortly thereafter.

Although the analysis of coordination games lends insights as to some of the factors behind ratification of the Montreal Protocol, it does not identify whether fully cooperative gains have been achieved. Recall that when continuous choices are allowed, coordination games have multiple matching-behavior equilibria. Elsewhere, Murdoch and Sandler (1997b) demonstrate that the initial requirements of the protocol as well as the actions taken by countries to curb CFCs emissions in 1989 are in keeping with a noncooperative Nash equilibrium.

Global Warming

Global warming stems from a greenhouse effect as trapped gases in the earth's atmosphere let sunlight through but absorb and trap infrared radiation, thereby raising the

---

[17] The multilateral fund supports the infrastructure needed for the treaty and provides scientific assistance to those needing aid.

mean temperature. Gases with this property are called greenhouse gases (GHGs) and include carbon dioxide (CO_2), CFCs, methane, ozone, and nitrous oxide. Carbon dioxide is a byproduct of the burning of fossil fuels. Tropical deforestation can also add large amounts of carbon to the atmosphere as cleared trees are burned or decomposed. Methane can come from mining and agricultural activities, whereas nitrous oxide is partly derived from the use of fertilizers.

Global warming, like ozone depletion, yields negative outputs that are nonrival among nations and nonexcludable, thus implying a summation technology whereby GHGs accumulate in an additive fashion. But if these two global commons problems share the same technology of aggregation, then why have treaty ratifications been so different? To date, nations have not come near to agreeing to limit GHGs emissions. The first major difference between global warming and ozone depletion involves the number of countries that would have to coordinate action for the presence of free riders to not undo the cooperator' restraints. In the right-hand half of Table 3.2, I list the major industrial-based emitters of CO_2. Emissions are again concentrated: the top three account for 50 percent, while the top twelve account for about 73 percent. But this is not the whole story. In Table 3.3, the major polluters of CO_2 from tropical deforestation are indicated. The top seventeen polluters account for the accumulation of 5,260,000 thousand metric tons of carbon emissions, or about 20 percent of the total from industry and land-use changes. Only India and Mexico are in both Table 3.2 and 3.3; hence, I have identified 27 significant emitters of carbon and have not included sources of methane or nitrous oxide.

Table 3.3. Major Polluters Of CO_2 From Land-Use Changes (Tropical Deforestation)

Country	Rank	Equivalent CO2 Emissions (000 metric tons)	Percent of World Total
Brazil	1	950,000	14.8
Indonesia	2	870,000	13.6
Columbia	3	420,000	6.6
Myanmar	4	380,000	5.9
Cote d'Ivoire	5	350,000	5.5
Thailand	6	290,000	4.5
Malaysia	7	280,000	4.4
Nigeria	8	270,000	4.2
Lao People's Dem Rep.	9	240,000	3.8
Mexico	10	200,000	3.1
Philippines	11	190,000	3.0
Ecuador	12	160,000	2.5
Vietnam	13	150,000	2.3
Peru	14	140,000	2.2
Zaire	15	130,000	2.0
Madagascar	16	120,000	1.9
India	16	120,000	1.9
Total		5,260,000	82.2
World		6,400,000	100.0

Source: World Resources Institute (1992, Table 24.2, pp. 348-49).

The latter pollutants are associated with some agrarian countries not in either table. To varying degrees, every country adds to global warming, whereas many countries do not add to ozone depletion (World Resources Institute 1992, Tables 24.1-24.2). Obviously, the large numbers required for coordination in global warming works against treaty formation. It also raises transaction costs.

A second inhibiting factor concerns the small expected gains from curbing global warming (see, e.g., Nordhaus, 1991). These gains are small owing, in part, to the uncertain impact of global warming on climate and rainfall. Much still needs to be learned in terms of carbon accumulation and its environmental impact. As a consequence, nations apply large discount factors to potential costs associated with global warming. This has been especially true for the U.S., which has not assumed a leadership role for this problem. Without leadership by the major players, adherence probabilities are independent and my pessimistic analysis applies.

A third factor is the small values associated with acting prior to achieving a minimal-sized group (i.e., the Bs are small). Self-imposed curtailment of carbon emissions may yield little net gain for even a significant-sized coalition, such as the European Community.

Acid Rain

Acid rain stems from the emission of sulfur dioxide (SO_2), sulfates, and nitrogen oxides (NO_x), which when released into the atmosphere can combine with water vapor and tropospheric ozone to form sulfuric and nitric acids. As the atmosphere performs self-cleansing process, acid precipitation results and threatens forest resources, lakes, rivers, coastal waters, and manmade structures. Sulfur emissions arise from the burning of fossil fuels, while nitrogen oxides derive from automobile emissions, fertilizers, and other sources. A primary source of sulfur emissions is from the generation of electric power. Since sulfur dioxide, sulfates, and nitrogen oxides emissions can travel over a thousand kilometers and remain aloft for up to eight days, acid rain poses a commons problem with transnational regional implications. But, unlike ozone and global warming, acid rain is a more localized problem with significant country-specific aspects.

An appropriate technology of public supply aggregation is the weighted sum, where weights indicate the proportion of sulfur emissions in country j deposited on country i's soil. Each country's deposition of, say, sulfur is set equal to a weighted sum of regional sulfur emissions by country. More formally, sulfur deposition in country i (G_i) equals

$$G_i = \sum_{j=1}^{n} \alpha_{ij} E_{ij} \qquad i = 1,\ldots,n \tag{3.12}$$

where α_{ij} is the fraction of country j's emissions (E_j) falling on country i's soil.[18] For the regional group as a whole, I have

$$\mathbf{G} = \mathbf{AE}, \tag{3.13}$$

---

[18] Another measure of α_{ij} can also be constructed. Depositions (emissions that land within a certain region) may be used as the divisor instead of emissions. In this case α_{ij} would be the fraction of country j's regional depositions that fall on country i's soil. This measure of α_{ij} is always greater than the the first measure of α_{ij} because regional depositions from a country are less than that country's total emissions.

in which **G** is an n × 1 vector $(G_1,...,G_n)$ of depositions, **A** is the n × n transport matrix of α_{ij}s, and **E** is an n × 1 vector $(E_1,...,E_n)$ of emissions. Similarly, each nation's reduction in depositions equals a weighted sum of regional emission cutbacks.[19] In the case of sulfur and NO_x, these weights have been determined empirically through monitoring stations, computer modeling, and statistical analysis for Europe (Eliassen and Saltbones 1983; Sandnes 1993).

The transport matrix of oxidized sulfur for 1990 is indicated for 27 European countries in Table 3.4, where the entries are the α_{ij}s and are in percentage terms, so that for, say, the Soviet Union (SUN), 83.6 percent of its own sulfur pollutants (that fall within the EMEP study region) fall on its own territory, and 16.4 percent land elsewhere in the study region.[20] 1.8 percent drops on Finland (FIN). Neither the columns nor the rows sum to 100% because some emissions land outside the 27 European countries and some depositions are from areas outside Europe. The Soviet Union is also affected by Finland (FIN) and Poland (POL), because 27.3 percent of Finland's pollution descends on the Soviet Union, while 12.6% of East Germany's sulfur emissions fall on the Soviet Union. With a few exceptions, a country receives the lion's share of its own pollution. The larger is the country, the larger is this share. Nearness also matters, because countries pollute downwind neighbors. These first two facts pave the way for bilateral and trilateral treaties. Transport matrices are not symmetric, since location, wind direction, and other

---

[19] For a formal model, see Mäler (1989) and Murdoch and Sandler (1997a).

[20] The Soviet Union gets only about 30% of its own total emissions (using the first measure) but it gets over 90% of its own emissions of the total that falls within the 27 countries (the second measure).

Table 3.4. Oxidized Sulfur Transport Matrix For 1990 (In Percentage Terms)

	Emitters:																										
	ALB	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
ALB	34.5	0.0	0.0	0.7	0.1	0.0	0.0	0.0	0.0	0.0	0.8	0.3	0.0	0.5	0.0	0.0	0.0	0.1	0.0	0.2	0.0	0.0	0.0	0.1	0.0	0.0	0.7
AUT	0.0	40.4	1.3	0.1	2.9	0.3	0.0	1.7	1.6	2.6	0.0	1.5	0.2	2.8	2.9	0.8	0.0	1.0	0.0	0.2	0.2	0.2	6.6	0.0	0.1	0.3	1.8
BEL	0.0	0.0	22.2	0.0	0.1	0.1	0.0	2.4	0.2	1.4	0.0	0.0	0.3	0.0	2.9	2.7	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.9	0.0
BGR	3.4	0.7	0.1	51.3	0.7	0.1	0.0	0.1	0.3	0.2	2.7	1.9	0.0	0.4	0.0	0.1	0.0	0.5	0.0	6.5	0.0	0.0	0.0	0.8	0.3	0.1	2.7
CSK	0.0	8.2	1.7	0.3	36.2	0.7	0.1	1.4	6.6	3.4	0.1	7.8	0.3	0.7	2.9	1.4	0.0	4.0	0.0	0.9	0.1	0.3	1.7	0.0	0.1	0.5	1.9
DNK	0.0	0.0	0.7	0.0	0.2	13.8	0.1	0.4	0.5	0.9	0.0	0.0	0.5	0.0	0.0	1.0	0.6	0.2	0.0	0.0	0.0	0.8	0.0	0.0	0.0	0.9	0.0
FIN	0.0	0.4	0.4	0.0	0.4	1.9	40.2	0.2	0.5	0.4	0.0	0.2	0.3	0.1	0.0	0.5	2.3	0.7	0.0	0.1	0.0	6.2	0.0	0.0	1.8	0.4	0.1
FRA	0.0	1.1	10.0	0.0	1.2	0.7	0.0	40.5	1.7	4.7	0.0	0.4	1.9	3.0	14.5	5.2	0.0	0.7	1.7	0.1	5.4	0.2	7.7	0.0	0.1	2.6	0.6
DDR	0.0	0.7	3.2	0.0	5.3	2.0	0.0	1.7	32.6	6.5	0.0	0.2	0.6	0.2	4.3	3.3	0.6	1.2	0.0	0.1	0.1	0.3	0.6	0.0	0.1	1.1	0.1
DEU	0.0	4.3	13.6	0.1	3.6	2.5	0.1	9.2	6.1	37.4	0.0	0.4	1.8	1.2	21.7	12.2	0.6	1.4	0.2	0.1	0.6	0.5	11.6	0.0	0.1	3.4	0.3
GRC	7.6	0.4	0.1	8.5	0.3	0.0	0.0	0.1	0.1	0.1	30.5	0.7	0.0	0.6	0.0	0.1	0.0	0.2	0.0	1.6	0.1	0.0	0.0	2.0	0.2	0.0	1.1
HUN	0.0	6.1	0.4	0.4	3.0	0.1	0.0	0.4	1.0	0.7	0.2	34.1	0.0	1.2	0.0	0.3	0.0	1.1	0.0	2.0	0.1	0.0	0.6	0.0	0.1	0.1	5.2
IRL	0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.2	0.1	0.1	0.0	0.0	28.3	0.0	0.0	0.2	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.6	0.0
ITA	1.7	5.4	1.1	0.6	1.8	0.1	0.0	3.4	1.2	1.5	1.1	2.3	0.2	41.6	1.4	0.8	0.0	0.9	0.7	0.5	1.1	0.2	12.2	0.1	0.1	0.3	5.0
LUX	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0	18.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
NLD	0.0	0.0	5.6	0.0	0.1	0.1	0.0	1.4	0.3	2.8	0.0	0.0	0.6	0.0	1.4	17.4	0.0	0.1	0.0	0.0	0.1	0.0	0.0	0.0	0.0	1.7	0.0
NOR	0.0	0.0	1.3	0.0	0.4	3.8	1.4	0.7	0.7	1.0	0.0	0.1	1.6	0.0	0.0	1.8	34.3	0.4	0.2	0.1	0.2	3.6	0.0	0.0	0.4	2.5	0.1
POL	0.0	4.3	3.8	0.4	13.2	4.9	0.6	2.1	16.6	6.5	0.1	5.1	1.0	0.6	4.3	4.1	1.1	44.5	0.0	1.3	0.2	2.1	1.1	0.0	0.8	1.8	1.8
PRT	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.2	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.0	0.0	37.6	0.0	1.9	0.0	0.0	0.0	0.0	0.1	0.0
ROM	2.5	2.5	0.4	5.5	3.0	0.4	0.2	0.4	1.3	0.7	0.9	9.7	0.2	0.9	0.0	0.5	0.0	2.2	0.0	52.0	0.1	0.2	0.0	0.5	1.1	0.2	7.1
ESP	0.0	0.0	0.9	0.0	0.1	0.1	0.0	2.4	0.3	0.5	0.0	0.1	0.5	0.5	1.4	0.7	0.0	0.1	18.6	0.0	48.3	0.0	0.6	0.0	0.0	0.6	0.2
SWE	0.0	0.4	1.5	0.0	1.0	11.5	6.5	0.8	1.8	2.0	0.0	0.3	1.0	0.0	1.4	2.0	12.6	1.5	0.0	0.2	0.1	37.3	0.0	0.0	0.7	2.0	0.1
CHE	0.0	0.7	0.6	0.0	0.3	0.0	0.0	2.2	0.3	0.9	0.0	0.1	0.2	2.3	1.4	0.5	0.0	0.2	0.2	0.0	0.3	0.0	46.4	0.0	0.0	0.2	0.2
TUR	0.8	0.4	0.1	3.8	0.4	0.1	0.0	0.1	0.2	0.2	5.3	0.9	0.0	0.2	0.0	0.1	0.0	0.5	0.0	2.0	0.0	0.0	0.0	59.6	1.1	0.1	0.5
SUN	1.7	7.1	6.3	5.8	14.1	13.0	27.3	3.4	12.6	8.2	2.3	15.6	2.2	1.4	5.8	6.9	6.9	27.0	0.2	18.5	0.4	15.1	1.7	8.2	83.6	4.0	5.9
GBR	0.0	0.0	1.5	0.0	0.2	0.5	0.0	1.1	0.3	0.7	0.0	0.0	11.3	0.0	0.0	1.8	0.6	0.1	0.2	0.0	0.3	0.2	0.0	0.0	0.0	33.1	0.0
YUG	11.8	8.2	0.7	6.3	2.8	0.3	0.1	1.0	1.4	1.1	1.5	9.2	0.2	6.3	1.4	0.5	0.0	1.4	0.2	3.3	0.3	0.2	1.7	0.3	0.2	0.2	50.4

Source: Sandnes (1993) and my calculation of the α_{ij}s based on the sulfur budget.

Abbreviations: ALB for Albania, AUT for Austria, BEL for Belgium, BGR for Bulgaria, CSK for Czechoslovakia, DNK for Denmark, FIN for Finland, FRA for France, DDR for East Germany, DEU for West Germany, GRC for Greece, HUN for Hungary, IRL for Ireland, ITA for Italy, LUX for Luxembourg, NLD for Netherlands, NOR for Norway, POL for Poland, PRT for Portugal, ROM foray, Romania, ESP for Spain, SWE for Sweden, CHE for Switzerland, TUR for Turkey, SUN for Soviet Union, GBR for the U.K., and YUG for Yugoslavia.

factors are crucial. In contrast, the transport matrix for a summation technology (e.g., ozone depletion) is symmetric and consists of all 1s, as each nation receives the total pollution from all others. This difference in transport matrices causes vastly different opportunities for free riding and country-specific effects when summation and weighted sum technologies are considered.

The two kinds of commons problems are really quite distinct; general prescriptions have little validity. Table 3.5 indicates sulfur emissions in thousands of metric tons of SO_2 for the greatest emitters in Europe during 1980, 1985, and 1989. In 1989, the top two polluters accounted for just under 40 percent of European and Soviet emissions, whereas the top nine polluters accounted for 86.5 percent of these emissions. Apparently, modest minimal-sized groups are needed for a treaty reducing such emissions. A second feature of the table is the decrease in emissions displayed by all but Spain between 1980 and 1989.

The game analysis of weighted sum technologies indicates that a coordination equilibrium may be difficult to achieve owing to modest gains derived from such an equilibrium. This does not mean that nations will not reduce emissions, because the Nash independent-adjustment equilibrium can be consistent with emission cutbacks. In the case of the ex-Soviet Union and the U.S., a large percentage of their sulfur deposition comes from their own emissions (Eliassen and Saltbones, 1983); hence, there is a motive for cutbacks even without a transnational treaty. Moreover, large downwind countries are motivated to play a leadership role.

Table 3.5. Sulfur Emissions (000 Metric Tons Of SO_2): 1980, 1985, 1989

Country	1980	1985	1989	1989 Percent of Europe & U.S.S.R.
U.S.S.R.	12,800	11,100	9,318	23.2
Germany[a]	8,200	7,400	6,710	16.7
Poland	4,100	4,300	3,910	9.7
U.K.	4,848	3,676	3,552	8.9
Spain	3,250	3,250	3,250	8.1
Czechoslovakia	3,100	3,150	2,800	7.0
Italy	3,800	2,504	2,410	6.0
France	3,510	1,846	1,520	3.8
Hungary	1,634	1,420	1,218	3.0
Total of Nine	—	—	34,688	86.5
Europe[b] & U.S.S.R.	—	—	40,104	100.0
U.S.	23,400	21,100	20,700[c]	—

Source: World Resources Institute (1992, Table 24.5, p. 24).

[a] Includes West and East Germany.

[b] Other European countries included Albania, Austria, Belgium, Bulgaria, Denmark, Finland, Greece, Iceland, Ireland, Luxembourg, the Netherlands, Norway, Portugal, Romania, Sweden, Switzerland, and Yugoslavia.

[c] Sulfur emissions for 1988.

The 1979 Convention on the Long-Range Transmission of Air Pollutants (henceforth called LRTAP) in Europe was the first formal agreement on acid-rain-causing pollutants. This treaty mandated scientific investigation and evaluation of the problem by establishing a system of monitoring stations throughout Europe (UNEP, 1991). It is these stations' data that are used to derive the weights for determining transnational deposition of sulfur. The LRTAP treaty was ratified on 16 March 1983 after the required sixteen nations signed. Given the distribution of pollution, sixteen appears to be a restrictive number of ratifiers; bilateral and trilateral treaties would have been appropriate for some countries. The most noteworthy agreement on sulfur emissions is the Helsinki Protocol (8 July 1985) to the LRTAP Convention. This protocol committed nations in North America and Europe to reduce sulfur emissions by at least 30 percent, based on 1980 levels, as soon as possible or by 1993 (UNEP, 1991).

Murdoch and Sandler (1997a) constructed a weighted sum model using an empirically determined transport matrix of weights for Europe. Their analysis indicated that reductions in sulfur emissions between 1980 and 1985, mandated by the Helsinki Protocol, was consistent with a noncooperative Nash equilibrium. It is noteworthy that these reductions were, for many countries, attained prior to the treaty being ratified. By the end of 1989, the European countries in Table 3.5 had reduced sulfur emissions on average by 22.8 percent from their 1980 baseline. This suggests that the treaty did not accomplish much in terms of a true cooperative equilibrium, a result consistent with the game theory analysis. Nations reduced sulfur emissions, because it was in their self-interest to do so. The treaty was written to codify these self-induced reductions.

Tropical Deforestation

Tropical forests house over half of the world species of plants and animals, so that the clearing of these forests would have a significant impact on the earth's genetic diversity. In addition, these forests sequester significant amounts of carbon, which could, if released, accelerate global warming. Tropical forests also provide a bequest value that the current generation worldwide derives from passing an asset on to a future generation. Thus, tropical forests yield global public goods. But these forests also give rise to localized public and private outputs to the host nation and their neighbors. Private outputs include timber and nontimber products. For host nations and neighbor states, rain forests provide local public goods in terms of watersheds, erosion control, localized climate effects, nutrient recycling, and bequest value. In short, the preservation of tropical forests produces multiple outputs; hence, joint products are present (Sandler, 1993).

From a coordination equilibrium perspective, two opposing forces are at work. On the negative side, the large number of participants required for a minimal-sized coalition restricts the achievement of a treaty. Table 3.3 indicates that at least seventeen nations are destroying their tropical forests in a significant manner. For global benefits, many developed countries that place a high value on the environment will have to be included in any agreement to support preservation if free riders are not to prosper. These large numbers of participants will inhibit the formation of a meaningful treaty. On the positive side, the presence of local benefits keeps the gains from individual action large in the absence of a fully coordinated equilibrium (i.e., the Bs in matrix b in Figure 3.1). These large gains limit the adherence probability and, thus, support treaty formation.

To date, there has been no significant agreement on the preservation of tropical forests. This is, indeed, unfortunate since about two percent of these forests are being cleared annually. At current rates of exploitation, these forests are apt to vanish in 50 years. The best hope is probably for a limited number of the most prosperous nations to strike an agreement with nations like Brazil, Ecuador, and Colombia with some of the largest forests.

Concluding Remarks

I have attempted to break with tradition by stressing the differences among problems of the transnational commons. In particular, problems differ based on the technology of public supply that applies. These diverse technologies imply different prognoses for coordinating actions among transnational groups. My analysis is tied to the theory of coordination games where minimal-sized coalitions are required and players are uncertain about their counterparts' intentions. The number of required participants, the patterns of payoffs, leadership possibilities, and the underlying technologies were shown to be crucial considerations when predicting the outcome of treaty formation. This chapter has identified factors behind the successful negotiations on stratospheric ozone depletion. Unfortunately, these favorable factors do not yet extend to global warming even though ozone depletion and global warming abide by a summation technology. In the case of acid rain, my analysis has been supportive of individual actions, but predicted that treaties would do little to codify reductions beyond those that nations would attempt anyway due to localized benefits from such actions. Finally, I identified factors behind the impasse on preserving tropical forests.

CHAPTER 4. SNAPSHOTS IN TIME: RESULTS OF A SIMPLE SPATIAL ECONOMETRIC MODEL

Introduction

I now turn from the general problems facing the construction and implementation of transnational commons treaties, to developing, constructing, and testing an empirical model that seeks to explain the differences between the international treaties that regulate sulfur and NO_x emissions. This chapter consists of five parts. In the first part I develop a theoretical model of sulfur and NO_x emission reductions that includes voluntary and nonvoluntary actions. Voluntary action concerns emission cutbacks beyond levels mandated in a protocol, whereas nonvoluntary action involves meeting mandated cutbacks. In the second part, an empirical model is constructed, derived from the theoretical model, that accounts for the spatial dispersion of emissions within the European sample countries. In the third section, the empirical specification is put through a number of tests using EMEP data for the 1980-90 period in an effort to refute the theoretical model. In the fourth section, the contrast in the two transboundary pollution problems is explained. In the last section, the results of testing the models are used to make projections of future sulfur and NO_x protocols.

A casual comparison of European emission data for sulfur and nitrogen oxides throughout the 1980s (Tuovinen et al., 1994; Tables 3.2 - 3.3) shows strikingly different patterns in the respective emissions. Most countries have met or exceeded the 30 percent mandated sulfur reductions from 1980 levels by the end of the decade, while some of these same countries were having a difficult time in reducing NO_x emission levels. But why are the two responses so different? This chapter 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 my analysis is to resist the temptation to lump together collective action problems even if they involve the same participants, because key ingredients—group size, the range of benefit or cost spillovers, and/or selective incentives—may differ (Olson, 1965; Sandler, 1992).

The analysis of the regression results indicates that the theoretical model leads to an empirical representation that yields reasonable results for sulfur, but less supportive 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. For NO_x, income has no clear-cut influence, whereas increased political freedoms inhibit pollution reductions owing to strategic behavior at the individual polluter level. My empirical results are in keeping with Barrett (1994) which demonstrated that treaties, containing more than a few participants, are unlikely to achieve much in cooperative gains. For groups the size of the Helsinki or Sofia Protocol, a Nash model of behavior is best suited to explain reductions as shown here.

The theoretical and empirical techniques developed in this chapter can be applied to a wide range of public good problems, drawn from environmental and public economics. Its analysis is especially germane for those problems where spillins have a spatial dimension -- e.g., recreation, police protection, and disease containment.

Theoretical Model

What follows is a simple model of voluntary and nonvoluntary emission reductions of a pollutant. The underlying model is a Nash subscription model, 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.[1] 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 I return to this issue when interpreting my empirical results.

The ith nation's strictly increasing, quasi-concave utility function is

$$U_i = U_i(y_i, \alpha_{ii}q_i + \tilde{Q}_i, E_i), \tag{4.1}$$

where y_i is the ith nation's consumption of the private numéraire good; q_i denotes the ith nation's reduced emissions between a base year and the current year of reference; α_{ii} is the

---

[1] On Nash subscription models for impure public goods, see McGuire (1990). For alternative pollution scenarios, Nash equilibrium behavior has been investigated by Barrett (1993) and Welsch (1993). These earlier subscription models did not include spatial dispersion, because it was not relevant to their problems.

fraction of the ith 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.[2] 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 after 1987 by

$$q_i^v = q_i - q_i^T = 0.7 \times (\text{1980 emission levels}) - \text{current emissions.} \tag{4.2}$$

Emission levels smaller than 70 percent of the 1980 emission level are considered to include voluntary reductions. By (4.2), total emission reductions in nation i, based on a base year level, equal

$$q_i = q_i^v + q_i^T. \tag{4.3}$$

But if $q_i^T = 0$, all reductions are voluntary.

Reduced spillins of pollution deposition in nation i, derived from other 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

$$\tilde{Q}_i = \sum_{j \neq i}^{n} \alpha_{ij} q_j = \sum_{j \neq i}^{n} \alpha_{ij} (q_j^v + q_j^T) \tag{4.4}$$

---

[2] Implicitly, we are assuming that reduced depositions are also a good proxy for improved ambient air quality.

for nation i, where α_{ij} is the fraction of nation j's emissions that falls on nation i. In (4.4), the index on the summation runs from j = 1 to 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 falls 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 depositions. Publicness arises from nonexcludability, not nonrivalry. If, instead, say 62 percent of a nation's emissions is deposited within the region and the remainder is 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:

$$m_i = y_i + p_i q_i^V + p_i q_i^T, \qquad (4.5)$$

where m_i is national income, the price of the private good, y_i, is unity, and p_i is the per-unit price of voluntary and nonvoluntary reductions. The model is kept simple—p_i does not differ between the two classes of emission reductions, and a parametric price is assumed.[3]

---

[3] The price or marginal cost of pollution reduction varies with the level of reduction. Our model, thus, can be viewed as linearizing the budget constraint within a neighborhood of the equilibrium, using the price associated with the equilibrating quantity. This is a standard procedure in applied studies (e.g., hedonic studies) for estimating a demand function when prices are variable.

With the use of equations (4.3)-(4.4), I can now state the maximization (subscription) problem for nation i:

$$\max_{q_i^v} U_i[y_i, \alpha_{ii}(q_i^v + q_i^T) + \sum_{j\neq i}^{n} \alpha_{ij}(q_j^v + q_j^T), E_i]$$
$$\text{subject to: } \begin{cases} m_i = y_i + p_i q_i^v + p_i q_i^T \\ \tilde{Q}_i \text{ and } q_i^T \text{ given} \end{cases} \tag{4.6}$$

A number of remarks are in order. 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 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. Owing to this last factor, the problem can be solved in two parts for positive and negative q_i^v; but in each case the Kuhn-Tucker conditions yield the same demand function. Fourth, exogenous factors include m_i, p_i, α_{ii}, q_i^T, $\tilde{Q}_i$, and E_i. As discussed earlier, E_i represents both environmental and political factors and acts as a shift variable. Fifth, if mandated levels, q_i^T, are zero, then the choice variable is q_i. Furthermore, the target level would then not be part of spillins—spillins would only be voluntary. Sixth, ambient air quality is proxied by total depositions, Q_i. I could also add q_i by itself as an addition to the utility function to better proxy improved ambient air quality, since any decrease in the country's own emission improves air quality as less particulate matter transverses the country's atmosphere. This addition would not, however, change the demand equations in (4.7) and (4.8); hence, it is not included here.

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

$$q_i^v = q_i^v[m_i, p_i, \alpha_{ii}, E_i, \sum_{j\neq i}^{n}\alpha_{ij}(q_j^v + q_j^T), q_i^T], \qquad \text{for } q_i^T > 0, \tag{4.7}$$

and

$$q_i^v = q_i^v(m_i, p_i, \alpha_{ii}, E_i, \sum_{j\neq i}^{n}\alpha_{ij}q_j^v), \qquad \text{for } q_i^T = 0, \tag{4.8}$$

Because the latter is a special case of the former, I focus my remarks on the empirical representation of the demand equation in (4.7). This equation applies to <u>each</u> country in the region (model). In order to develop a model that can be empirically tested, I will use a Taylor series expansion of (4.7) rewritten in a more general form as

$$q_i^v = f(x_{1i}, x_{2i}, \ldots, x_{mi}), \tag{4.9}$$

where m equals the number of explanatory variables. Using equilibrium values, $e_{1i}, e_{2i}, \ldots, e_{mi}$, as expansion points, the resulting Taylor series becomes,

$$\begin{aligned} q_i^v = f^* &+ \sum_{j=1}^{m}\left(\frac{\partial f^*}{\partial x_j}\right)(x_{ji} - e_{ji}) \\ &+ \frac{1}{2}\sum_{k=1}^{m}\sum_{j=1}^{m}\left(\frac{\partial^2 f^*}{\partial x_k \partial x_j}\right)(x_{ji} - e_{ji})(x_{ki} - e_{ki}) + \cdots \end{aligned} \tag{4.10}$$

with $f^* = f(e_{1i}, e_{2i}, \ldots, e_{mi})$. This can be simplified by keeping just the linear terms, giving

$$q_i^v = \beta_0 + \sum_{j=1}^{m}\beta_j x_{ji} + \text{remainder}, \tag{4.11}$$

where $\beta_0 = f^* - \sum_{j=1}^{m} \frac{\partial f^*}{\partial x_j}(e_{ji})$ and $\beta_j = \frac{\partial f^*}{\partial x_j}$. Therefore, using the original variables of (4.7), the linear approximation of the ith nations demand function for q_i^V becomes:

$$q_i^V = \beta_0 + \beta_1 m_i + \beta_2 p_i + \beta_3 \alpha_{ii} + \beta_4 E_i + \rho \sum_{j \neq i}^{n} \alpha_{ij}(q_j^V + q_j^T) + \gamma q_i^T + \varepsilon_i . \qquad i = 1, \ldots, n \tag{4.12}$$

where β_0 is a constant, β_1, β_2, β_3, β_4, ρ and γ are coefficients, and ε_i is an error (remainder) term.

To simplify notation, I revert to a vector representation where $\mathbf{q}^V$ is the n × 1 vector $(q_1^V, \ldots, q_n^V)'$; $\mathbf{q}^T$ is the n × 1 vector $(q_1^T, \ldots, q_n^T)'$, $\tilde{\mathbf{A}}$ is an n × n transport matrix, **X** is an n × 5 matrix of parameters, $\boldsymbol{\beta}$ is a 5 × 1 vector $(\beta_0, \ldots, \beta_4)'$, and ε is an n × 1 vector $(\varepsilon_1, \ldots, \varepsilon_n)'$ of error terms. The ith row of the **X** matrix is $(1, m_i, p_i, \alpha_{ii}, E_i)$. Finally, I must distinguish the **A** transport matrix from the $\tilde{\mathbf{A}}$ transport matrix. The latter includes zeros in the diagonal places, so that a country's own q_i^V only appears on the left-hand side of its equation. The remaining terms in $\tilde{\mathbf{A}}$ are the α_{ij}s. Thus, the equation system in (4.12) can be written in matrix form as

$$\mathbf{q}^V = \rho \tilde{\mathbf{A}} \mathbf{q}^V + \mathbf{X}\boldsymbol{\beta} + \rho \tilde{\mathbf{A}} \mathbf{q}^T + \gamma \mathbf{q}^T + \varepsilon. \tag{4.13}$$

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.

Empirical Model

Equation (4.7) is a representation of a country's demand function for emission reductions. I hypothesize that the data observed in the real world are generated from this type of behavioral relationship and that the relationship provides a good representation of past behavior. To test this claim, I attempt to refute it. The methodology involves using observations on the relevant variables to estimate the parameters of approximations to the function, such as the one presented in equation (4.12). These parameter estimates (the βs, ρ, and γ) can then be checked for logical consistency when interpreted as demand function parameters.

To estimate equation (4.12) for sulfur and NO_x reductions, I need data on these measures for the European nations that participated in the LRTAP Convention on Long-Range Transboundary Air Pollution. For my empirical sample, Canada, Iceland, and the US are left out owing to my focus on European deposition, while Liechtenstein is excluded because it does not appear in the EMEP transport matrix as the grid is too coarse. Finally, Turkey is dropped because the data is inconsistent between different sources. I have 25 countries that generate useful observations for the study.

The "snapshot in time model" of this chapter estimates demand functions for all nations, and thus assumes that the demand functions for each nation are identical, when controlling for measurable shift parameters. The estimated relationship must be interpreted as an "average" equation derived from the sample.

Variable Definitions

Measures of q_i^v and q_i^T

Emissions by year are obtained from EMEP (Tuovinen et al., 1994). 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 my models represents the voluntary reductions (in 1000 tons) of sulfur or NO_x emissions. With respect to sulfur, I 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, I compute the q_i^v before the Helsinki Protocol as the difference S80 – S85 and refer to it as S8085. To estimate demand behavior after the Helsinki Protocol, I compute voluntary reductions as $q_i^v = 0.7 \times S80 - S90$, which I refer to as S8090. My choice of 1990 as the ending year to compute the change is somewhat arbitrary; however, it is motivated by my desire to end the study period prior to the dramatic political changes in Eastern Europe and to provide some symmetry with respect to S8085. My qualitative conclusions are unaffected by this choice; i.e., using any ending year between 1988 – 1991, I 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 rate of emission reductions specified in the Helsinki Protocol; i.e., 0.3 × S80. I emphasize that countries with high rates of emissions in 1980 will necessarily face greater targets. As TARGET increases, I consequently expect that, ceteris paribus, voluntary contributions will decrease.

For NO_x, there are two measures of voluntary contributions. The first is NO8087 = NO80 – NO87, and the second is NO8890 = NO88 – NO90.[4] 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.

Voluntary reductions in sulfur and NO_x, expressed in percentages, are presented for selected years in Table 4.1. I first focus on percentage reduction in sulfur emissions between 1980 and 1985 (%SUL85) based on 1980 emissions, in which the entire reduction, if positive, is voluntary. Ten of the twenty-five nations had achieved the subsequently targeted reductions at the time that the Helsinki Protocol was adopted. Another six nations (Denmark, West Germany, Norway, Portugal, Switzerland, and the

---

[4] Murdoch, Sandler, and Sargent (1994, Table 7A) present the NO_x results with alternative definitions of voluntary behavior. The results presented later are robust with respect to these alternative definitions.

Table 4.1. Percentage Reductions in Voluntary Sulfur and NO$_x$ Emissions by Country

Country	%SUL85	%SUL90	%SUL92[a]	%NOX87	%NOX90	%NOX92[a]
1. Austria	50.75	47.39	48.89	4.88	5.13	7.69
2. Belgium	45.41	16.38	15.89	32.81	-12.46	-12.79
3. Bulgaria	-12.88	-28.54	-10.98	0.00	9.62	34.38
4. Czechoslovakia	10.32	-8.79	-0.92	16.28	2.08	11.71
5. Denmark	23.89	30.18	16.02	-11.72	7.21	7.21
6. Finland	34.59	25.48	36.78	-2.27	-7.41	-10.74
7. France	55.96	32.25	28.96	10.59	-7.36	-11.04
8. E. Germany	-25.58	-41.63	-41.63[b]	-13.56	5.97	5.97[b]
9. W. Germany	24.98	40.57	40.57[b]	1.78	11.17	11.17[b]
10. Greece	-25.00	-55.00	-55.00	0.00	0.00	0.00
11. Hungary	13.97	8.11	8.11	-1.10	13.77	13.77
12. Ireland	36.94	-5.68	-15.59	-57.53	-17.39	-13.04
13. Italy	34.11	12.63	12.63	-14.86	-3.59	-3.59
14. Luxembourg	33.33	3.33	3.33	17.39	0.00	0.00
15. Netherlands	40.77	25.36	26.65	-2.01	1.25	1.97
16. Norway	28.57	31.43	35.71	-25.14	-1.75	-0.44
17. Poland	-4.88	-8.29	-3.07	-2.00	16.34	21.24
18. Portugal	25.56	-6.69	-6.69	30.12	-5.17	-5.17
19. Romania	0.00	-3.00	-3.00	0.00	0.00	0.00
20. Spain	34.04	0.24	0.24	11.68	0.00	0.00
21. Sweden	43.85	37.31	37.31	-2.86	6.26	6.26
22. Switzerland	23.81	20.79	20.79	-2.04	8.00	12.50
23. Soviet Union	13.05	3.12	3.12[b]	-23.44	-7.84	-7.84[b]
24. United Kingdom	23.97	-7.05	-7.05	-10.03	-7.27	-7.27
25. Yugoslavia	-14.88	-43.34	-43.34[b]	-25.71	4.55	4.55[b]
Average	20.59	3.98	4.83	-2.75	0.84	2.66

Source: Sandnes (1993).

[a] For countries with identical emissions reported in 1990 and 1992, data were either extrapolated or estimated by Sandnes (1993).

[b] Based on the 1990 value because the country's borders changed in 1991.

Notes:

%SUL85 = Reduction in voluntary sulfur emissions from 1980 to 1985 as a percent of 1980 emissions.
%SUL90 = Reduction in voluntary sulfur emissions from 1980 to 1990 as a percent of 1980 emissions.
%SUL92 = Reduction in voluntary sulfur emissions from 1980 to 1992 as a percent of 1980 emissions.
%NOX87 = Reduction in voluntary NO$_x$ emissions from 1980 to 1987 as a percent of 1980 emissions.
%NOX90 = Reduction in voluntary NO$_x$ emissions from 1987 to 1990 as a percent of 1987 emissions.
%NOX92 = Reduction in voluntary NO$_x$ emissions from 1987 to 1992 as a percent of 1987 emissions.

UK) had achieved at least a reduction of 23 percent by the end of 1985. Czechoslovakia, Hungary, and the Soviet Union had already reduced emissions by 10-14 percent at the time of the treaty adoption. The overwhelming number of protocol participants had met the treaty's mandate or were well on their way to meeting it by the time of adoption. Mean reductions were 20.59 percent prior to the treaty. In the next column, I display the voluntary percentage reduction in sulfur emissions in 1990 based on 1980 emissions (%SUL90), where the 30 percent target is accounted for, so that positive levels indicate an overachievement of the mandate. Fifteen sample nations had exceeded mandated levels by 1990 and another five were within 9 percentage points of the target.

A much different pattern of voluntary cutbacks for NO_x emerged prior to the Sofia Protocol. Voluntary reductions in NO_x emissions between 1980 and 1987 as a percentage of 1980 emissions (%NOX87) were positive for only eight nations in Table 4.1. It is also noteworthy that these were much more modest than sulfur on average. Overall mean reductions were -2.75 percent. Additionally, only a couple nations displayed a monotonic pattern of cutbacks from 1980 to 1987 when yearly observations are consulted (see Murdoch, Sandler, and Sargent, 1994, Figure 2). By 1990 shortly after the adoption of the Sofia Protocol, all but nine sample nations had maintained NO_x emissions at or below 1987 levels. A positive, but small, mean reduction in NO_x emissions was evident.

Measures of m_i

To measure a nation's income, I use the Gross Domestic Product (GDP), which poses some problems. Perhaps, the most difficult problem is to find cross-nationally comparable figures. This is especially true in my case because the sample of nations includes traditional market and nonmarket economies. Another problem is that there are many different sources for GDP estimates in the nonmarket economies. A third problem is that I want GDP estimates for different slices of time; thus, I need estimates comparable across nations and through time. Fortunately, Summers and Heston (1988) have produced the Penn World Tables which address each of the above problems (available from the National Bureau of Economic Research's WWW address). But because of the political changes that occurred in 1989, data for East Germany, Romania, and the USSR does not exist for 1990. Therefore, 1990 uses the 1989 estimates for those countries.

Measures of α_{ii}

The percentage of a country's sulfur or NO_x emissions that falls within its own borders (OWNSUL or OWNNOX) is calculated from the 1990 Budget of Oxidized Sulfur or Nitrogen in Tuovinen et al. (1994).[5] 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 1990, Belgium's total sulfur emissions measured 221,500 tons. Of this, 65.6 percent (145,300 tons) fell within the countries of the EMEP study region. I can identify where 145,300 tons of Belgian emissions fell by examining the EMEP's 1990 Budget of Oxidized Sulfur. For example, 42,500 tons fell in Belgium itself; 18,500 tons, France; and 25,300

---

[5] The econometric model also uses the 1985 budgets from Tuovinen et al. (1994) but there is no significant difference in the results.

tons, West Germany. To find OWNSUL, I first divide the country's depositions within its own borders by the country's depositions within the countries of the study area. For Belgium, this calculation is 42,500 / 145,300 = 0.292. An identical procedure is used to calculate OWNNOX. OWNSUL is the measure of α_{ii} for sulfur and OWNNOX is the measure of α_{ii} for NO_x.

In Figure 4.1, I display the α_{ii} values, measured along the vertical axis, for the 25 sample nations. These α_{ii} values are based on depositions within the 25 countries of the EMEP study region and are calculated in the same way as the example for Belgium. For every nation, α_{ii} is greater for sulfur than for NO_x. Thus, self-deposition of pollutants is more characteristic of sulfur and, as such, there are more country-specific gains from reducing sulfur rather than NO_x emissions -- i.e., selective incentives are greater.

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 my case, are

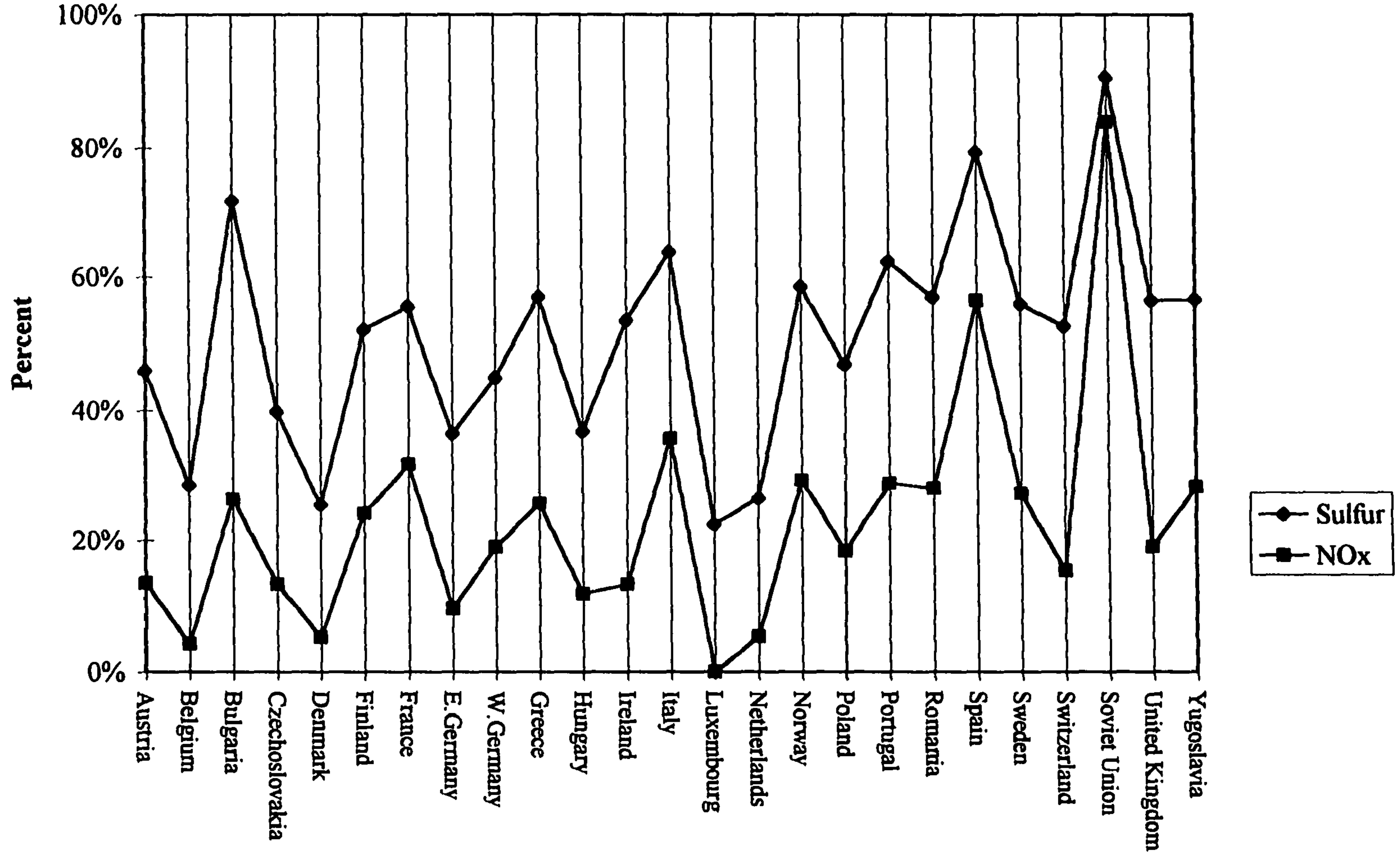

Figure 4.1. Percentage of 1990 Depositions that Falls Within a Nation's Borders

25 by 25 matrices. For example, the seventh row of the 1990 matrix represents the depositions in France and the second column indicates the emissions from Belgium. Building on the earlier example for Belgium, the entry in the seventh row, second column in the Budget of Oxidised Sulfur is 18,500 tons. This means that from the 145,000 tons emitted by Belgium that fell within the selected countries, 18,500 tons fell within the borders of France. Thus, the empirical realization of α_{72} is 18,500 / 145,000 = 0.127, which implies that when Belgium voluntarily reduces its emissions so that the depositions within the study area fall by, say, 100 units, France is expected to realize a reduction of 12.7 units of depositions.

Using a similar method, I can find a matrix of α_{ij}s. With zeros along the diagonal, this matrix is the empirical realization of $\tilde{A}$ and allows us to calculate the voluntary reductions in spillins for France or country 7 as $SPILL_7 = \sum_{j\neq i}^{25} \alpha_{7j} q_j^v$, where $\alpha_{77} = 0$. Alternatively, I can represent the calculation of the 25 by 1 SPILL vector as $\tilde{A} \times \mathbf{q}^v$, where $\mathbf{q}^v$ is the 25 by 1 vector of voluntary contributions. The calculation is similar with respect to TSPILL.

Measures of p_i

We want a measure for the price of emission cutbacks in the various scenarios that reflects each country's energy pathway (i.e., its actual and anticipated pattern of energy generation), its level of emission reductions, and the marginal cost (MC) associated with the actual level of emission reductions. The Regional Acidification Information and

Simulation (RAINS) model, version 6.1, of the International Institute for Applied Systems Analysis (IIASA) (1993) contains MC curves by countries for different years. For my pre-Helsinki estimates, I use the RAINS MC curves for each country to find the MC associated with the level of sulfur reductions in 1985, taken from Tuovinen et al. (1994). For the Soviet Union alone, I calculate the relevant MC using an aggregate of the regions of the former USSR. I assume that the MC, while different among countries, is parametric at the actual (equilibrium) level of emission cutbacks. For the post-Helsinki estimates, I employ 1990 sulfur reduction levels for the sample countries from Tuovinen, et al. (1994) and the 1990 MC curves from the RAINS model to calculate the relevant MC levels for each country. Henceforth, I call MC levels for sulfur, MCSUL.[6]

I follow the same procedure for obtaining the MC measures for each country and different snapshots in time for NO_x. For the pre-Sofia period, emission cutbacks are based on NO8087, which are then used in conjunction with the RAINS MC curves for 1985 to ascertain the MC levels for each sample country. (There is no RAINS MC curve for 1987). For the post-Sofia period, emission cutbacks are based on NO8890, which are then used in conjunction with the RAINS MC curves for 1990 to compute the MC levels for the estimates (MCNOX).[7]

---

[6] The marginal cost curves provided by RAINS are not continuous functions, but step functions. So another measure of price I calculated was the change in MC that would occur if more reductions were undertaken by a nation. These MC estimates were the ones reported in Table 4.2.

[7] More information on control costs and emission reductions can be found in Emission Control Costs and their Influence on International Emission Reduction Strategies (United Nations, 1991b).

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. I attempt to control for this influence by using Freedom House's index of civil liberties and index of political freedoms (Gastil, 1989 and McColm, 1991). 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. I convert the sum of the two indices into a binary variable called FREE, which equals 1 for a sum less than or equal to 4, and 0 otherwise. Voluntary contributions are anticipated to respond positively to FREE. I use 1985 FREE indices for the S8085 estimates and 1990 indices for all of the other estimates.

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 the potential for large damages may demand more emission reductions to protect its resources. Thus, a nation with relatively large forest cover or a large susceptible population may desire more reductions to minimize the potential damages to their forests and exposed populations. To control for these influences, I examine two measures of potential damage. The first is PFOREST, which is the percentage of a nation's land area classified as forest and woodland (UNEP, 1993). Depositions of sulfur and NO_x either directly, or indirectly through acid rain, are expected to have a harmful effect on a nation's forests and woodlands. Damage to alpine lakes and forests was the first indication of acid rain's damaging effects. Therefore, one expects that the greater the percentage of a country that is covered by forest, the greater the incentive to reduce emission levels of SO_2. It is also possible that since NO_x is also a component of acid rain, reductions of NO_x might also occur. But the effects of NO_x are much less clear since nitrogen is a plant fertilizer. Studies do not give an unqualified answer at this point. Therefore I expect PFOREST to have a stronger effect in the sulfur than the nitrogen regressions.

For potential damages from ambient air quality degradation attributable to NO_x and sulfur, I employ a measure of the population most at risk-- the percentage of a nation's population living in urban areas. This variable is denoted as URBAN and is taken from the 1985 and 1990 editions of The World Almanac and Book of Facts. Adverse health effects are caused by ozone pollution and the damage to buildings and monuments results from acid rain. It is hypothesized that the greater the percentage of urbanization, the more likely a country will be to reduce its emissions of sulfur and nitrogen oxides. One would expect the significance of URBAN to be higher in the nitrogen regressions than in the sulfur regressions because NO_x is the primary chemical leading to formation of ozone.

I am particularly interested in the third set of demand shift influences, namely, international policy actions. I hypothesize that the countries that ratified the Helsinki and Sofia Protocols are more apt to have a different demand relationship when compared to countries that did not.[8] In addition, one would expect that countries that delayed ratification would have been less likely to make emission reductions than countries that ratified the protocols shortly after their signing. In order to capture these effects, the variables HELSINKI and SOFIA are used (and were obtained from the Air Pollution Studies series published by the United Nations). They consist of the number of years since a protocol has been ratified. For example, a country ratifying the Helsinki Protocol in 1986 would receive a '4' while a country ratifying the protocol in 1989 would receive a '1.' A country that had not ratified the protocol by 1989 would receive a '0.'

An additional shift variable has been added to the demand function for NO_x emission reductions. In 1958 the EEC established an agreement designed to reduce motor vehicle emissions. This agreement consisted of a large number of regulations. Some nations have passed none of these regulations while several countries have passed many of them (United Nations, 1992). The EEC variable represents how many of eight laws, singled out as the most relevant, have been passed by the European nations. This variable is designed to be a proxy for institutional behavior in regards to NO_x reductions.

Econometric Model

Using the above-defined variables, I can re-specify the basic regression equation in (4.12) for voluntary sulfur reductions in the post-Helsinki period as,

---

[8] The source for the ratification data is personal correspondence with the Treaty Section, Office of Legal Affairs, United Nations. These data are available in Murdoch, Sandler, and Sargent (1994).

$$\begin{aligned} \mathrm{S8090}_i = \beta_0 + \rho_1\mathrm{SPILL}_i + \rho_2\mathrm{TSPILL}_i + \beta_1\mathrm{GDP}_i + \beta_2\mathrm{MCSUL}_i + \beta_3\mathrm{OWNSUL}_i \\ + \beta_4\mathrm{FREE}_i + \beta_5\mathrm{HELSINKI}_i + \beta_6\mathrm{URBAN}_i + \gamma\mathrm{TARGET}_i + \varepsilon_I, \qquad (4.14) \end{aligned}$$

where S8090 is the dependent variable and i denotes the country. In (4.14), the ρ_is, 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 s^2. Equation (4.14) should be viewed as representative of my regression models; i.e., I estimate numerous similar expressions by changing the dependent variable and/or the set of independent variables.

Our empirical task is to find estimates for the ρ_is, β_is, γ, and s^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 S8090 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) S8090 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 $t - 1^{st}$ observation. In my case, I 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, I appeal to the method of maximum likelihood (ML), which is appropriate if the ε_is follow the normal distribution. An analysis of the normal probability plot of the ML residuals (not shown) suggests that the normality assumption is reasonable for the models represented by equation (4.14).[9] Thus, I 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 4.2, while the NO_x models are given in Table 4.3.[10] A quick scan of the two tables reveals that the sulfur data fit the models better than the NO_x data. In fact, approximately 67 percent of the coefficients in the sulfur models are statistically significant ($\alpha = 0.10$, one-tail test using the cumulative normal distribution) with the anticipated signs, while 37 percent are significant with the anticipated signs in the NO_x models.[11] Despite "looking good," I still must guard against making incorrect inferences in the sulfur models. Thus, I considered four sets of regression diagnostic procedures. The procedures were performed on model 5 presented in Table 4.2, because, as I argue below, it is one of the best models.

---

[9] See Murdoch, Sandler, and Sargent (1997). The normal probability plot is also called the normal Q-Q plot (Cleveland, 1993, Chapter 2).

[10] The parameter on $TSPILL_i$ (ρ_2) is insignificant in all models (see Murdoch, Sandler, and Sargent, 1997). Thus, I have dropped this variable when presenting the main results.

[11] The one-tail test is used since the theory underlying the models (discussed in chapters 2, 3, and 4) predicts what the expected sign is for each of the variables.

Table 4.2. **Maximum Likelihood Estimates of the Spatial Model for SO_2 Emission Reductions (Z-values in Parenthesis)**

	Pre-Helsinki			Post-Helsinki		
Variables	(1)	(2)	(3)	(4)	(5)	(6)
SPILL	-0.18	-0.23	-0.27	-0.91	-1.05	-1.03
	(-0.99)	(-1.20)	(-1.45)	(-3.29)	(-3.70)	(-3.56)
GDP	0.80	0.74	0.39	1.84	1.86	1.82
	(3.14)	(2.77)	(1.03)	(7.34)	(7.62)	(6.91)
MCSUL	-0.67	-0.63	-0.49	-0.16	-0.18	-0.16
	(-2.05)	(-1.93)	(-1.45)	(-1.11)	(-1.28)	(-1.16)
OWNSUL	24.10	27.82	50.48	21.61	25.47	29.79
	(1.64)	(1.82)	(2.14)	(2.19)	(2.55)	(2.19)
FREE	844.86	815.20	908.59	663.62	642.87	655.82
	(4.30)	(4.08)	(4.38)	(4.19)	(4.15)	(4.17)
TARGET				-1.03	-1.08	-1.09
				(-6.30)	(-6.66)	(-6.66)
HELSINKI				141.00	70.86	91.30
				(1.25)	(0.59)	(0.71)
URBAN		3.99	6.16		4.72	4.42
		(0.73)	(1.11)		(1.20)	(1.10)
PFOREST			-9.68			-2.43
			(-1.22)			(-0.48)
Constant	-856.22	-1160.52	-1605.33	-983.18	-1308.72	-1338.69
	(-1.99)	(-1.97)	(-2.38)	(-3.34)	(-3.35)	(-3.39)
-Log Likelihood.	181.23	180.97	180.26	171.95	171.29	171.18
R^2	0.70	0.70	0.71	0.75	0.72	0.72

Table 4.3. Maximum Likelihood Estimates of the Spatial Model for NO_x Emission Reductions (Z-values in Parenthesis)

	PRE-SOFIA			POST-SOFIA		
Variables	(1)	(2)	(3)	(4)	(5)	(6)
SPILL	-0.80 (-2.66)	-0.70 (-2.26)	-0.67 (-2.11)	-1.63 (-4.34)	-1.64 (-4.83)	-1.54 (-4.36)
GDP	-0.32 (-2.35)	-0.38 (-2.73)	-0.36 (-2.22)	0.22 (1.77)	0.28 (1.86)	0.36 (2.24)
MCNOX	0.14 (0.62)	0.18 (0.82)	0.15 (0.66)	0.00 (-0.36)	-0.01 (-0.55)	-0.01 (-0.59)
OWNNOX	-4.22 (-0.61)	-1.27 (-0.18)	-2.37 (-0.29)	-23.35 (-3.20)	-26.35 (-2.98)	-28.90 (-3.24)
FREE	-98.25 (-1.61)	-87.02 (-1.46)	-80.85 (-1.29)	1.95 (0.03)	31.19 (0.46)	45.75 (0.67)
SOFIA				52.22 (1.25)	32.57 (0.74)	26.34 (0.60)
URBAN		2.37 (1.28)	2.32 (1.24)		1.83 (0.82)	2.32 (1.04)
PFOREST			0.63 (0.29)		3.23 (1.47)	4.15 (1.83)
EEC						-14.74 (-1.26)
Constant	39.21 (0.94)	-120.38 (-0.91)	-129.77 (-0.96)	52.03 (1.02)	-143.85 (-0.84)	-154.34 (-0.92)
-Log-likelihood	155.48	154.71	154.67	159.49	158.18	157.42
R^2	0.65	0.68	0.68	0.41	0.67	0.66

The first procedure involves visually examining the scatterplot of the ML residuals and normal probability plot. The second procedure is a test for heteroskedasticity. Using the ML residuals and the continuous independent variables, the Breusch-Pagan c^2 (and Spatial B-P) equals 6.28. The p-value for the test is 0.51, indicating that I fail to reject the null hypothesis of homoskedasticity.[12] Thus, there is little reason to doubt the constant variance assumption. The third procedure is a Lagrange Multiplier test for spatial error dependence (similar to the Durbin-Watson test for serial correlation in time-series models). The value was 0.168, giving a p-value of 0.68. Therefore, the assumption of no spatial error dependence cannot be rejected.[13]

Because only a fraction of the total land area in the Soviet Union is covered under the Helsinki Protocol, I suspect that this country should not be treated like the others. For the fourth procedure, I re-estimated the model dropping the Soviet Union. The results are similar to those presented in Table 4.2; except that the HELSINKI coefficient is now significant and the URBAN estimate is negative; hence, there does not appear to be sufficient evidence supporting dropping this nation.

Empirical Results

The post-Helsinki regressions results reported in Table 4.2 give support for the theoretical model. Eight of the nine variables (SPILL, GDP, MCSUL, OWNSUL, FREE, TARGET, HELSINKI, PFOREST, and URBAN) have the expected signs. Of the seven

---

[12] The Breusch-Pagan tests for all other models in the Sulfur regressions were not significant and only model four had a p-value less than model 5.

[13] All other models in Table 4.2 exhibited no spatial dependence in the error term, either.

variables used in all three post-Helsinki models, all except MCSUL and HELSINKI are significant at the 99% confidence level. The rest of this section will examine the results in more detail, comparing and contrasting pre- and post-treaty behavior in emission reductions for sulfur.

In the pre-Helsinki period, the SPILL terms for each of the three models has the correct sign, but is significant at the 10% level only in model 3. However, in all three of the post-Helsinki models, the SPILL term is negative and highly significant, possessing a larger magnitude than in the pre-Helsinki models. Therefore it appears that voluntary reductions in the post-Helsinki period are more susceptible to strategic behavior. The post-Helsinki results generally confirm the model of voluntary behavior that underlies my 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.[14] Ceteris paribus, when spillins of SO_2 are reduced by 1 kt, a country will increase its emissions (i.e. decrease its reductions) of SO_2 that land within the study region by 1.05 kt (using model 5). This result accords with the Nash behavior model presented earlier. This partial effect is dramatically different than the gross effect as measured by the correlation coefficient. For the post-Helsinki period, I

---

[14] This is a partial measure that indicates the influence of reduced SPILL on voluntary reductions, holding all other influences constant. Since some of these influences are supportive of voluntary cutbacks, the negative estimates on the SPILL term is entirely consistent with nations having positive overall cutbacks owing to these other influences.

calculated the correlation between SPILL and S8090 to be -0.29, which suggests no strong association.

The positive value for GDP in the pre- and post-Helsinki period indicates that the existence of an income effect for emission reduction is a reasonable hypothesis. Model 2 in Table 4.2 indicates that with all other factors held constant, for every one billion dollar increase in a country's GDP there is a 0.74 kiloton (kt) reduction in that country's SO_2 emissions in the pre-Helsinki period. The contribution of GDP to emission reductions is even more pronounced in the post-Helsinki period. For every billion dollar increase in a country's GDP the result is a 1.86 kt reduction in SO_2 emissions (using model 5). Using the coefficient on GDP (the change in voluntary emission reductions resulting from a $1 billion change in GDP) and multiplying it by the average value of GDP over the average value of emission reductions gives the income elasticity of emission reductions. Environmental quality (as represented by reductions in SO_2) is an income inelastic good in the pre-Helsinki period (income elasticity of demand = 0.6) but a highly income elastic good in the post-Helsinki period (income elasticity of demand = 20.8). Therefore, it appears that in the post-Helsinki period, citizens of wealthy nations came to value environmental quality more (or citizens in the less wealthy nations began to value it less).

FREE performs as predicted in both periods. The positive coefficient on FREE indicates that countries defined as free had SO_2 emission reductions that <u>Ceteris paribus</u>, were about 800-900 kt more than those of other non-free nations in the pre-Helsinki period and about 650 kt more in the post-Helsinki period. It appears that political and civil freedoms led to greater environmental concern and larger emission reductions.

OWNSUL (expressed as a fraction between 0 and 1), which is positive and significant at the 5% level in model 2 of Table 4.2, indicates that ceteris paribus, for every 1% increase in the amount of its own emissions falling on its own soil, a country reduced its emissions by about 28 kt. Similar results occur in the post-Helsinki period. Here, the coefficient on OWNSUL indicates that for every 1% increase in a country's own deposition rate, there is a reduction of between 22 and 30 kt in SO_2 emissions. These results are therefore consistent across time indicating that no significant shift in behavior took place in regards to OWNSUL or FREE during the period under study.

MCSUL (the marginal cost of emission reductions) has the predicted negative sign in both time periods but the values are only significant in the pre-Helsinki period and model 5 of the post-Helsinki period.[15]

While URBAN is of the correct sign, it is unfortunately not significant. The positive coefficient on URBAN accords with my hypothesis. Other measures designed to take health effects into account, such as the percentage of the population over 65 or the percentage under 15 (and the proportion of both younger and older populations), performed no better than URBAN. Thus, suggesting that the pre-Helsinki contributions were not motivated by health concerns.

---

[15] Because of the large marginal cost differences between countries, the square root of MCSUL was entered into the model, but the results were not significantly different than those reported.

PFOREST also did not perform well as predicted. In both the pre- and post-treaty periods, it was negative but not significant. More importantly, the introduction of this variable altered the results in the pre-Helsinki model. First, SPILL became significant, but the coefficient for GDP became insignificant. One likely explanation for these dramatic effects would be multicollinearity between PFOREST and some other variables, especially with GDP, but a test of simple correlations between the variables failed to turn up any significant multicollinearity.

Fortunately, the inclusion of PFOREST in the post-Helsinki model did not have any significant effects as it did in the pre-Helsinki models. Other measures designed to measure emission reductions as a response to forest damage due to acid rain, such as a nation's critical load, total forested area, and percentage of injured conifers and broadleaf trees, were either insignificant or of the wrong sign.

Several new variables are included in the post-Helsinki regression results. TARGET (the target level of emissions) was negative and significant at the 1 percent level in all three of the models. The results indicate that the higher the target level of emissions, the less the reduction in a country's voluntary level of emission reductions. In fact, for every one kt increase in the target level, the result was a reduction of voluntary emissions between 1.03 and 1.09 kt. Ceteris paribus, nations that faced a greater target level of reductions are achieving less in voluntary reductions. Another additional explanatory variable, HELSINKI, did not turn out to be significant but the sign was positive, which if significant, would have indicated that nations ratifying the Helsinki Protocol early were more willing to make emission reductions beyond the target than nations that did not ratify the protocol or delayed ratification.

When comparing the pre-Helsinki (model 2) to the post-Helsinki (model 5) estimates, I find that the size of the spillin response increased quite substantially in the post-Helsinki sample. Apparently, emission reductions beyond the mandated 30 percent cut are subjected to greater strategic behavior than the initial pre-Helsinki cuts. The slightly increased income effect may suggest that the post-Helsinki reductions are more discretionary, perhaps owing to the lack of a political constraint that mandates additional cuts. Because of the poor performance of PFOREST and URBAN in the pre-and post-Helsinki estimates for sulfur, model 2 of both periods provides the most parsimonious result.

A comparison of the log-likelihood values gives little support in favor of a particular model in either period. I prefer model 5 primarily because I believe that the susceptible population is theoretically an important variable. Similarly, model 2 is preferred for the pre-Helsinki period. Henceforth, models 2 and 5 are viewed as the best representations of the data.

The regression results, for NO_x emission reductions, reported in Table 4.3 offer much less support for the voluntary reduction model, but some interesting patterns emerge. In both pre- and post-Sofia regressions, the SPILL terms are significant, negative, and of even greater magnitude, implying that the strategic response to foreign-originated depositions is greater with respect to the voluntary reductions in NO_x. <u>Ceteris</u>

paribus, a reduction of 1 kt of NO_x depositions from other countries results in an increase in NO_x emissions between 0.7 and 0.8 kt tons of NO_x in the pre-Sofia period and an increase between 1.5 and 1.6 kt in the post-Sofia period. Again, strategic behavior appears to have increased in later periods as it did for sulfur, giving evidence that the subscription model is applicable to NO_x emissions reductions as well as sulfur.

In the pre-Sofia period GDP is negative and significant, a reversal of the results for the sulfur models. The results are remarkably consistent. On average, for every one billion dollar increase in GDP, a country will increase its emissions (decrease its emission reductions) by 0.32 to 0.38 kt of NO_x. However, in the post-Sofia period, the results are quite different. GDP is positive and significant (at better than the 5 percent level) in all three models. The behavior of FREE is also unusual in both periods. It is noteworthy that the FREE dummy variable is negative, and significant in all pre-Sofia models, hinting that nations with the greatest civil and political liberties may voluntarily reduce emissions less on average when compared to nations with fewer liberties. But FREE is positive and not significant in the second period making my conclusion less certain.[16]

These two changes in GDP and FREE are the most dramatic difference from the sulfur models and require some explanation. Sulfur emissions are predominately from power plants and other stationary sources, while NO_x emissions are mainly due to mobile sources. FREE countries have a relatively larger number of vehicles on the road making NO_x emissions much more difficult to control than in the FREE countries where private

---

[16] In contrast, Murdoch, Sandler, and Sargent (1997) found FREE to be negative and significant in the post-Sofia period but not significant in the pre-Sofia period.

ownership of vehicles is uncommon. Likewise countries with low levels of GDP may not depend on motor vehicle transport as much as higher income countries do (perhaps as a result of a less developed infrastructure). Therefore, it may be easier for countries that depend less on motor vehicle transport to make greater cuts in their NO_x emissions. It seems that further investigation of the link between the number of motor vehicles, political freedom, and a country's GDP would be useful.

Another unexpected result is the curious behavior of OWNNOX. Like that for OWNSUL, I hypothesize that this value should be positive, indicating that the more of a country's emissions which fall on itself, the more likely the country will be to make emission cutbacks. However, the value of this variable is consistently negative in both pre- and post-Sofia periods.

The marginal cost of reducing NO_x emissions (MCNOX) is not a significant explanatory variable in either the pre- or post-Sofia periods, although in the post-Sofia period, all estimates have the correct negative sign. It would appear that the cost of pollution control was not a significant determinant of emission reduction of either NO_x or Sulfur.

URBAN has the correct sign but is significant in only one of the pre-Sofia periods. I maintain the hypothesis that more urbanized countries have reduced emissions of NO_x by a larger percentage than less urbanized countries, but another variable will be needed for stronger evidence, such as city levels of ozone. Other measures of human health, such as the percentage of a country's population above age 60 or below age 15, produced results that were not significant or of the wrong sign. Certainly then, human health effects were not the driving force behind either the Sofia or Helsinki Protocols.

One might expect a high correlation between the urbanization level (URBAN), GDP, and FREE, but this is not proven out by the data. Using 1985 data, the correlation between GDP, URBAN and FREE is -0.20 and +0.20 respectively, while that between URBAN and FREE is -0.26. Likewise, the correlation between PFOREST and other variables is small. PFOREST and GDP have a -0.20 correlation, while PFOREST and URBAN have a correlation of -0.16.

The introduction of PFOREST into the model gives a positive result that is significant only in the second period. This may indicate that nations are becoming more aware of the damage acid rain is doing to forests. However, if this hypothesis were true, similar results should be apparent in the post-Helsinki results. There is little evidence then for my hypothesis that PFOREST would have the strongest (positive) effect in the sulfur regressions, while URBAN would play a more significant role in the nitrogen regressions.

The variable, EEC, turned out to be negative but not significant. However, I may possibly explain this result as follows: nations signing this treaty (which dates back to 1958) may have already made substantial cutbacks in motor-vehicle emissions. Another possibility is that nations that have signed this law have many vehicles and therefore have a difficult time cutting back. Looking at the actual data though does not shed any light on this because there seems to be no pattern. For example while Romania and Yugoslavia have passed four and five of the laws, Greece and Denmark have passed none.

For symmetry with the sulfur regressions, model 2 is preferred for the NO_x regressions, since URBAN and PFOREST contribute little explanatory power to the model. Although the PFOREST coefficient is positive and significant in model 6, its inclusion does not significantly improve the model, so there is little statistical evidence favoring a particular model. Therefore model 5 is also preferred in the post-Sofia period.

Given the above results it is not surprising that the increases in the log-likelihood function value from -155.48, -154.71, to -154.67 (models 1, 2 and 3) and -159.49, -158.18, to -157.42 (models 4, 5, and 6) indicate that no model is statistically superior.

Tests for heteroskedasticity using the Breusch-Pagan and Spatial Breusch-Pagan tests detected no significant problems in the pre-Sofia regressions. However, there was substantial heteroskedasticity in the post-Sofia period. This problem was corrected by using a routine in SpaceStat that expressed the error variance as a linear function of OWNNOX.[17] The Lagrange Multiplier test on spatial error dependence in each models resulted in values that were not significant. Therefore, the hypothesis of a normally distributed error term could not be rejected.

A contrast of the sulfur and NO_x results yields 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

---

[17] Specifically, $Var[\varepsilon] = Zv$, where $Var[\varepsilon]$ is an N by 1 column vector of the error variances, Z is an N by 1 matrix of the squared values of OWNNOX, and v is the corresponding vector of coefficients.

are nonsupportive for NO_x. 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. 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. A relatively large fraction of a nation's sulfur emission falls on itself, while for NO_x, the emissions travel much further or dissipate into the atmosphere. 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 of NO_x.

In comparison with the results reported in Murdoch, Sandler, and Sargent (1994) (MSS), the results are qualitatively similar in many respects but there are some notable differences that may be due to several causes. First, different regression software was used. The results in this chapter were derived using the SpaceStat program from West Virginia University's Regional Research Institute, while the MSS paper uses a program written in SAS.[18]

Second, much of the data used in this dissertation comes from different sources than that used by MSS. Emission data and the budgets for both sulfur and nitrogen are taken from the 1994 Report of the Norwegian Meteorological Institute while MSS use the Institute's 1993 Report. GDP rather than GNP is used as a measure of national income, and the change in the marginal cost (MC) of the next level of emission reduction is used

---

[18] More information on spatial econometrics programs can be found in Anselin and Hudack (1992).

rather than the marginal cost. Although MSS use the square root of both GDP and MC, the results are similar to those of the untransformed variables. Zero values for MC prevented the use of a log transformation.

Third, some variables used by MSS were dropped and new ones added. The percentage of the population over age 65 (POP65) has been dropped and replaced by URBAN. HELSINKI and SOFIA were changed from binary variables to discrete integer variables. Finally, EEC was a new variable added to the post-Sofia regression.[19]

Policy Implications

In Table 4.1, presented earlier, a majority of nations had either met or were close to meeting the 30 percent reductions (from 1980 levels) in SO_2 emissions by the time of the signing of the Helsinki Protocol. 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 countries, the cutbacks already achieved served as a blueprint for the treaty stipulations. A similar pattern regarding the Sofia Protocol emerged in the case of NO_x. Since the reductions were slow to achieve and modest, the stipulated reductions in the Sofia Protocol were also modest--maintaining 1987 emission levels.

If this pattern of voluntary reductions preceding the framing of treaties continues, then a policy prediction follows from Table 4.1. In the case of sulfur, the percent of

---

[19] The change in GDP was another explanatory variable used in the models, but is not included in the models because it is not theoretically justified. The coefficient of this variable was expected to be negative because periods of economic expansion should increase emissions of sulfur and NO_x. The coefficient did turn out to be negative in all the models but was only significant in the post-Helsinki period.

voluntary sulfur emission reduction achieved in 1992 (%SUL92) is on average 4.8 percent beyond the targeted reductions of the Helsinki Protocol. Ten nations have achieved voluntary reductions greater than 15 percent beyond the 30 percent target. Thus, a new, stronger protocol should 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, I can be much less sanguine. At the end of 1992, reductions from 1987 levels are 2.66 percent (on average) for the 25 sample nations in Table 4.1. Subsequent protocols on NO_x will take a longer 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 (United Nations, 1992, p. 48).

Our prediction of a stronger protocol on sulfur emissions is born out by the Oslo Protocol drafted on 14 June 1994, but as of March 1996 still unratified. This protocol mandates stricter percentage reductions from 1980 levels than the Helsinki Protocol for most treaty countries by the year 2000. (United Nations, 1994, p. 15). Unlike earlier protocols, percentage reductions vary by country in the Oslo Protocol. Countries with greater current reductions are given stricter targets, consistent with the spirit of our hypothesis. No stricter protocol for NO_x has yet been drafted.

Because a greater fraction of NO_x can be transferred outside the treaty region, there is 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 boundaries. A similar recommendation does not follow for sulfur. 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.

Another 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 individual freedoms have to be traded off for more centralized control over NO_x polluters. 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.

Yet another policy 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.

Conclusion

Two different experiences emerge when the econometric model is applied. For sulfur reductions, the model performs reasonably well, thus supporting my 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. Voluntary cutbacks in 1992 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 my 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. Thus, two collective action problems that have some similarities do not require the same policy prescriptions. 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.

CHAPTER 5. CHANGES IN TIME: RESULTS OF A SPATIAL SUR MODEL

Introduction To Space-Time Models

A logical extension of the model in the previous chapter is to take time, as well as space, into account. Instead of simply looking at "snapshots in time" and comparing them, a time-series cross-section model can take into account the temporal as well as the spatial components of changes in air pollution reductions. This allows one to look for changes in the European nations' behavior over the course of several years. The changes over time in the coefficients and standard errors of a variable in the regression allow one to judge whether there have been changes in that variable's impact over time and whether these changes are significantly different from one year to the next. As in chapter 4, a one-tail test using the cumulative normal distribution with $\alpha = 0.10$ is used to test for significance of the coefficients. The one-tail test is used because the theory underlying the models used in chapters 4 and 5 indicates the expected signs for each of the variables.

This new model will allow me to examine several questions that could not be asked using the models in the last chapter. First, have nations behaved less strategically as time has passed? Specifically, have the nations behaved more or less cooperatively after the signing of either the Helsinki or Sofia Protocol? Second, has new scientific knowledge of environmental and health effects of sulfur and NO_x depositions over the last decade caused nations to alter their behavior during the 1980's? Third, have income and political freedom become more significant determinants of emission reduction over time and has the magnitude of their influence on emission reduction changed? Fourth, are nations that ratify a protocol sooner rather than later more likely to make voluntary emission reductions than nations who ratify the protocol later? Fifth, does the size of the target level of emissions play less of a role in voluntary emission reductions as the years pass? And sixth, did the marginal cost of emission reduction play a more significant role in voluntary reductions in the years following the ratification of the Helsinki and Sofia Protocols?

Some of these questions can be answered but some others cannot. A confident answer to any of the questions depends on how significant the coefficients are. As before, many of the variables in the sulfur model give consistent results and are significant. However, the NO_x model results do not provide definite answers to many of the questions, since the coefficients are often not consistent over time and lack significance. Clearly, there is room for future research on these questions.

Before looking at the results, a model must be found that can account for both spatial and time series components. In looking for a model, one of two approaches can be chosen. First, models that analyze both cross-section and time-series data can be modified to take account of spatial correlation and spatially lagged dependent variables, or second, a spatial autoregressive model can have a time component added to it (Stoffer, 1985; 1986). The two approaches are not mutually exclusive, but only a convenient way to examine a variety of models. For reasons discussed in the theoretical section, I choose the Spatial Seemingly Unrelated Regression (Spatial SUR) model discussed by Anselin

(1992), which is suited to investigating Nash behavior. For increased explanatory power, it includes a spatially lagged dependent variable with the coefficients of the explanatory variable allowed to vary across time but held constant in space.

The body of this chapter consists of five sections. The next section discusses how the theoretical model of the previous chapter can be changed to incorporate a time-series component. The following section consists of a brief summary of econometric models that are used for panel data sets and how they can be modified to deal with spatial autocorrelation. In the ensuing section, the model is discussed. The fourth section examines the empirical results from the regressions and the concluding section is devoted to contrasting the results from the two models and what can be learned from the results.

The Theoretical Model

The theoretical model for the last chapter was used to examine two distinct periods of time for the sulfur and NO_x models. Although these periods of time were determined by the signing dates of the Helsinki and Sofia Protocols, the data for SO_2 and NO_x emission reductions is continuous from 1985 on. Therefore, it is possible to make a more complete use of the data. One way to do this is to develop another spatial econometric model that can handle panel data (i.e. cross-section time-series data).

There are several complications in extending the theoretical model of the previous chapter so that it can handle time-series and cross-section data. The model, as before, is based on a Nash subscription model that explains voluntary and nonvoluntary emission reductions of SO_2 and NO_x. Emission reductions are treated as impure public goods and all countries in the model are assumed to be both emitters and recipients of these emissions. Again, all countries benefit to varying degrees from emission reductions in their own country and from other countries' emission reductions. Each country is assumed to maximize the welfare of its own citizens each year and ignore welfare effects on citizens of other countries.

But the new model requires the consideration of other factors that did not come into play in the earlier models. Naturally, the utility function is of the same form for each one year period as it is for the longer periods of time used in the last chapter. But should a nation be expected to maximize utility by discounting future benefits and costs? The utility of future GDP and emission reductions is less than the utility derived from current ones. On the other hand, the net present value of emission reductions today is greater than the net present value of emission reductions a year from now if costs are held constant. To maximize utility over several years, one must consider using net present value, discounting future costs and benefits.

The information needed to solve an intertemporal optimization problem requires data beyond the scope of what is now available. It would be necessary to know which nations first proposed the pollution control treaties and the requirements. Each nation also places different estimates on the uncertainty of future pollution control technology and evaluates the likelihood of damage to its forests and buildings differently. Finally, one would need to know a nation's estimate of future emissions from other countries and if any had formed possible strategies for punishing treaty defectors.

Fortunately, I am working with regression models that deal only with short, discrete periods of time. This means less concern needs to be placed on the issues of discounting, uncertainty, and intertemporal optimization. Because a nation's decision on emission reductions is reversible, less weight needs to be placed on the questions of utility from future levels of GDP or the utility of future emission reductions, compared to models which cover long periods of time, and when decisions are assumed not to change.

In addition, several of the independent variables do not change significantly during a year. Nations categorized as FREE did not change between 1980 and 1989, while the integer value of civil and political liberties is constant for most countries during this time, at most changing by only one or two points. The percentage of a nation's land classified as forest and the percentage of the population classified as urban, changes even less.

Finally, because of the short decision periods, uncertainty with regards to: 1) depositions from other countries, 2) future costs of pollution control, and 3) the impact of pollution control on GDP, are not expected to have significant effects in the model.

A reasonable hypothesis is that all nation's voluntary emission reduction decisions can be made yearly. Therefore, decision makers need only concern themselves with current variables when making their utility maximizing decision. This is a reasonable assumption because emission reduction decisions are unlikely to be based upon future estimates of GDP, future marginal costs, or future spillins from other countries since the decision makers expect to have the opportunity to make another decision in one year.

Therefore, for current work, the same theoretical model (with small modifications in notation) is appropriate. The utility function of the i^{th} nation at time t is assumed to be strictly increasing and quasi-concave and can be written as

$$U_{it} = U_{it}\,(y_{it}, \alpha_{ii}q_{it} + \tilde{Q}_{it}, E_{it}), \tag{5.1}$$

where y_{it} is the i^{th} nation's consumption of the private numéraire good at time t; q_{it} represents the i^{th} nation's emission reductions for that year. It follows then that the term $\alpha_{ii}q_{it}$ represents the benefits, in terms of emission reductions, that nation i receives in time t by reducing its emissions by q_{it}. Likewise, $\tilde{Q}_{it}$ represents the benefits or "spillins" to nation i during time t resulting from emission reductions in all other nations. Finally, E_{it} is a vector of environmental and political factors in nation i at time t.

Voluntary reductions for country i at time t are calculated the same way as in the previous chapter as are the α_{ii}s and α_{ij}s. Each nation faces the same budget constraint for each period,

$$m_{it} = y_{it} + p_{it}q_{it} \tag{5.2}$$

and q_{it} consists of both voluntary q_{it}^{v} and nonvoluntary q_{i}^{T} emissions. The maximization problem for country i at time t now becomes

$$\max_{q_{it}^{v}}\; U_{it}[y_{it}, \alpha_{ii}(q_{it}^{v} + q_{i}^{T}) + \sum_{j\neq i}^{n}\alpha_{ij}\,(q_{jt}^{v} + q_{j}^{T}), E_{it}]$$

$$\text{subject to: } \begin{cases} m_{it} = y_{it} + p_{it}q_{it}^{v} + p_{it}q_{i}^{T} \\ \tilde{Q}_{it} \text{ and } q_{i}^{T} \text{ given} \end{cases} \tag{5.3}$$

The solution to the maximization problem is again based on the assumption of Nash behavior by each nation so that each nation chooses its best response given the spillins from other nations, $\tilde{Q}_{it}$.

From the first-order conditions of the optimization problem, I can express the i^{th} nation's demand for q_{it}^{v}, in terms of the exogenous variables, as

$$q_{it}^{v} = q_{it}^{v}[m_{it}, p_{it}, \alpha_{ii}, E_{it}, \sum_{j\neq i}^{n}\alpha_{ij}(q_{jt}^{v} + q_{j}^{T}), q_{i}^{T}], \qquad \text{for } q_{i}^{T} > 0, \tag{5.4}$$

and

$$q_{it}^{v} = q_{it}^{v}(m_{it}, p_{it}, \alpha_{ii}, E_{it}, \sum_{j\neq i}^{n}\alpha_{ij}q_{jt}^{v}), \qquad \text{for } q_{i}^{T} = 0. \tag{5.5}$$

As before, my model is based on the empirical representation of the demand equation in (5.4), since the demand equation in (5.5) is a special case of (5.4). This equation applies to <u>each</u> country in the region for each time period, t. Again, a Taylor series expansion of (5.4) is necessary to develop a model that can be empirically tested. For simplicity, I rewrite (5.4) in a more general form as

$$q_{it}^{v} = f(x_{1it}, x_{2it}, \ldots, x_{mit}), \tag{5.6}$$

where m equals the number of explanatory variables. Using equilibrium values, e_{1it}, e_{2it}, ..., e_{mit}, as expansion points, the resulting Taylor series becomes,

$$\begin{aligned} q_{it}^{v} &= f^{*} + \sum_{j=1}^{m}(\frac{\partial f^{*}}{\partial x_{tj}})(x_{jit} - e_{jit}) \\ &+ \frac{1}{2}\sum_{k=1}^{m}\sum_{j=1}^{m}(\frac{\partial^{2} f^{*}}{\partial x_{kt}\partial x_{jt}})(x_{jit} - e_{jit})(x_{kit} - e_{kit}) + \cdots \end{aligned} \tag{5.7}$$

with $f^{*} = f(e_{1it}, e_{2it}, \ldots, e_{mit})$. This can be simplified by keeping just the linear terms, giving

$$q_{it}^{v} = \beta_{0t} + \sum_{j=1}^{m} \beta_{jt} x_{jit} + \text{remainder}, \tag{5.8}$$

where $\beta_0 = f^{*} - \sum_{j=1}^{m} \frac{\partial f^{*}}{\partial x_{jt}}(e_{jit})$ and $\beta_{jt} = \frac{\partial f^{*}}{\partial x_{jt}}$. Therefore, using the original variables of (5.4), the linear approximation of the i^{th} nations demand function for q_{it}^{v} becomes:

$$\begin{aligned} q_{it}^{v} &= \beta_{0t} + \beta_{1t} m_{it} + \beta_{2t} p_{it} + \beta_{3t} \alpha_{ii} + \beta_{4t} E_{it} \\ &\quad + \rho_t \sum_{j \neq i}^{n} \alpha_{ij} (q_{jt}^{v} + q_j^{T}) + \gamma_t q_i^{T} + \varepsilon_{it}. \qquad i = 1, \ldots, n \end{aligned} \tag{5.9}$$

where β_{0t} is a constant, β_{1t}, β_{2t}, β_{3t}, β_{4t}, ρ_t and γ_t are coefficients, and ε_{it} is an error (remainder) term.

However, the result is more complicated than the previous chapter. Therefore, I will first give a brief review of space-time models which should help in understanding how to use the resulting Taylor series to construct an econometric model.

Econometric Review of Space-Time Models

The spatial autoregressive model used in the previous chapter was of the form,

$$\mathbf{q} = \rho \tilde{\mathbf{A}} \mathbf{q} + \mathbf{X}\beta + \varepsilon. \tag{5.10}$$

where $\mathbf{q}$ was a 25 × 1 vector of countries. $\tilde{\mathbf{A}}$ was a 25 × 25 matrix of spatial weights with the diagonal elements = 0. The coefficient for the $\tilde{\mathbf{A}}$ matrix was ρ, while $\mathbf{X}$ was a 25 × k matrix of independent variables and β was a k × 1 vector of coefficients. The error term, ε, was a 25 × 1 vector of normally distributed error terms.

The autoregressive model can be written in identical mathematical form to the spatial autoregressive model as,

$$\mathbf{q} = \gamma\mathbf{L}\mathbf{q} + \mathbf{X}\beta + \varepsilon. \qquad (5.11)$$

Here, **L** is a t x t matrix of time lags (with the diagonal elements = 0) for the dependent variable **q**, which consists of t observations, and γ is the weight placed on each of the time lags.[1] Notice that the classical linear regression model can be obtained by setting either ρ or $\gamma = 0$, giving,

$$\mathbf{q} = \mathbf{X}\beta + \varepsilon \qquad \text{where } \varepsilon \sim N(\mathbf{0}, \sigma^2). \qquad (5.12)$$

When the time dimension is added to the classical linear regression model (5.12), the result is the space-time model used for panel data studies,

$$q_{it} = \mathbf{x}'_{it}\beta_{it} + \varepsilon_{it}, \qquad (5.13)$$

where q_{it} is the dependent variable for nation i at time t, $\mathbf{x}_{it}$ is a vector of observations, β_{it} is a vector of coefficients, and ε_{it} is the error term with $E[\varepsilon_{it}] = 0$ and $E[\varepsilon_{it}\varepsilon_{js}] \neq 0$. In this model the error covariance matrix can take on different forms depending on whether $i = j$ or $t = s$. Each case is summarized in Table 5.1.

In order to completely specify the spatial econometric model, some decision must be made about the form the error term will take. The most common method is to impose constraints on the error term, but to insure that the constraints are not arbitrary, model specification tests should be used to help determine if these constraints are appropriate (see Anselin, 1988).

---

[1] In the spatial autoregressive model, ρ is commonly a single element so that each nation is treated identically, but in the autoregressive model, the coefficient for each time lag is expected to be different. Therefore, the model is more often written with γ_t', which is a 1 × t vector of weights for each time lag.

Table 5.1. Different Cases of the Error Covariance Matrix for the General Spatial Autoregressive Model

	$t = s$		$t \neq s$	
$i = j$	$E[\varepsilon_{it}^2] = \sigma^2$	constant variance		
	$E[\varepsilon_{it}^2] = \sigma^2_i$	spatial heterogeneity		
	$E[\varepsilon_{it}^2] = \sigma^2_t$	time-wise heterogeneity	$E[\varepsilon_{it}\varepsilon_{is}] = \sigma^2_{ts}(i)$	time-wise correlation
	$E[\varepsilon_{it}^2] = \sigma^2_{it}$	space-time heterogeneity		
$i \neq j$	$E[\varepsilon_{it}\varepsilon_{jt}] = \sigma^2_{ij}(t)$	contemporaneous correlation	$E[\varepsilon_{it}\varepsilon_{js}] = \sigma^2_{ij}(s)$	space-time correlation

Several types of space-time models can be obtained from (5.13) by constraining β across space and/or time. If β is constrained across space and time, then

$$q_{it} = \mathbf{x}_{it}'\beta + \varepsilon_{it} \qquad \text{(pooled cross section time series model).} \tag{5.14}$$

If however, β is constrained across time,

$$q_{it} = \mathbf{x}_{it}'\beta_i + \varepsilon_{it} \qquad \text{(SUR model).} \tag{5.15}$$

For β constrained across space, the result is:

$$q_{it} = \mathbf{x}_{it}'\beta_t + \varepsilon_{it} \qquad \text{(Spatial SUR model).} \tag{5.16}$$

Finally, adding a spatially lagged dependent variable to the spatial SUR model, gives

$$q_{it} = \rho_t\tilde{\mathbf{A}}\mathbf{q}_t + \mathbf{x}_{it}'\beta_t + \varepsilon_{it}. \tag{5.17}$$

The above cases are summarized in Table 5.2.

Table 5.2. Space-time Models derived from the General Spatial Autoregressive Model

		β unconstrained across time	β constrained across time
β unconstrained across space	no spatially lagged dependent variable	$q_{it} = \mathbf{x}'_{it}\beta_{it} + \varepsilon_{it}$ (general model)	$q_{it} = \mathbf{x}'_{it}\beta_i + \varepsilon_{it}$ (SUR model)
	with a spatially lagged dependent variable	$q_{it} = \rho_{it}\bar{\mathbf{A}}q_{it} + \mathbf{x}'_{it}\beta_{it} + \varepsilon_{it}$	$q_{it} = \rho_t\bar{\mathbf{A}}q_t + \mathbf{x}'_{it}\beta_i + \varepsilon_{it}$
β constrained across space	no spatially lagged dependent variable	$q_{it} = \mathbf{x}'_{it}\beta_t + \varepsilon_{it}$ (spatial SUR model)	$q_{it} = \mathbf{x}'_{it}\beta + \varepsilon_{it}$ pooled cross-section time-series model
	with a spatially lagged dependent variable	$q_{it} = \rho_t\bar{\mathbf{A}}q_t + \mathbf{x}'_{it}\beta_t + \varepsilon_{it}$	$q_{it} = \rho_t\bar{\mathbf{A}}q_t + \mathbf{x}'_{it}\beta + \varepsilon_{it}$

Equation (5.17) is the most appropriate model for my purposes. Although further modifications to this spatial model are possible by constraining the coefficients and/or intercepts, I will use the model without any additional constraints.

The Spatial SUR Model

To make the concepts easier to understand, I will apply the spatial SUR model with a spatially lagged dependent variable (5.17) to a data set with n nations and two time periods. The model can be written out as:

$$\begin{bmatrix} \mathbf{q}_{t_1} \\ \mathbf{q}_{t_2} \end{bmatrix} = \begin{bmatrix} \rho_{t_1} & 0 \\ 0 & \rho_{t_2} \end{bmatrix} \otimes \begin{bmatrix} 0 & \alpha_{12} & \cdots & \alpha_{1n} \\ \alpha_{21} & 0 & \cdots & \alpha_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ \alpha_{n1} & \alpha_{n2} & \cdots & 0 \end{bmatrix} \begin{bmatrix} \mathbf{q}_{t_1} \\ \mathbf{q}_{t_2} \end{bmatrix} + \begin{bmatrix} \mathbf{X}_{t_1} & \mathbf{0} \\ \mathbf{0} & \mathbf{X}_{t_2} \end{bmatrix} \begin{bmatrix} \beta_{t_1} \\ \beta_{t_2} \end{bmatrix} + \begin{bmatrix} \varepsilon_{t_1} \\ \varepsilon_{t_2} \end{bmatrix}, \tag{5.18}$$

where $\mathbf{q}_{t_i}$ is an n × 1 vector of dependent variables at time t_i, $\mathbf{X}_{t_i}$ is an n × k vector of independent variables at time t_i, β_{t_i} is a k × 1 vector of coefficients for the independent variables in each time period (the number of independent variables may also be different in each time period), and ε_{t_i} is an n × 1 vector of error terms.

The Kronecker product of the ρ and $\tilde{\mathbf{A}}$ matrices allows a different weight to be placed on the $\tilde{\mathbf{A}}$ matrix during each time period. It is also possible that the $\tilde{\mathbf{A}}$ matrix may be different for each time period. This will not occur when the weights are based on distances between countries, but for the model I am using, the spatial weight matrix is based partially on meteorological conditions that vary from year to year. Spatial weight matrices have been developed for each year by the Norwegian Meteorological Institute. Fortunately, one can use a single spatial weight matrix averaged over time since countries do not know in advance what that year's matrix will be. They will instead make their decisions based on the expected spatial weight matrix. Furthermore, the spatial weight matrices are virtually identical from year to year when expressed as percentages rather than as tons of the pollutant.

My spatial SUR model uses data from 25 countries and six time periods. Therefore, the demand equation for voluntary emission reductions given in (5.9) can be written more precisely as,

$$q_{it}^{v} = \rho_t \sum_{j \neq i}^{n} \alpha_{ij} (q_{jt}^{v} + q_j^{T}) + \beta_{0t} + \beta_{1t} m_i + \beta_{2t} p_i + \beta_{3t} \alpha_{ii} + \beta_{4t} E_i + \gamma_t \, q_i^{T} + \varepsilon_{it}$$

$$i, j = 1, \ldots, 25 \text{ and } t = 1980, 1985, 1986, \ldots, 1990 \qquad (5.19)$$

where β_{0t} is a constant, β_{it}s are coefficients, ε_{it} is an error term, and ρ_t and γ_t are also coefficients. If (5.19) is written in vector notation, the result is,

$$\begin{bmatrix} \mathbf{q}_{t_1}^{v} \\ \mathbf{q}_{t_2}^{v} \\ \vdots \\ \mathbf{q}_{t_6}^{v} \end{bmatrix} = \begin{bmatrix} \rho_{t_1} & 0 & \cdots & 0 \\ 0 & \rho_{t_2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \rho_{t_6} \end{bmatrix} \otimes \begin{bmatrix} 0 & \alpha_{12} & \cdots & \alpha_{1\,25} \\ \alpha_{21} & 0 & \cdots & \alpha_{2\,25} \\ \vdots & \vdots & \ddots & \vdots \\ \alpha_{25\,1} & \alpha_{25\,2} & \cdots & 0 \end{bmatrix} \begin{bmatrix} \mathbf{q}_{t_1}^{v} + \mathbf{q}^{T} \\ \mathbf{q}_{t_2}^{v} + \mathbf{q}^{T} \\ \vdots \\ \mathbf{q}_{t_6}^{v} + \mathbf{q}^{T} \end{bmatrix}$$

$$+ \begin{bmatrix} \mathbf{X}_{t_1} & \mathbf{0} & \cdots & \mathbf{0} \\ \mathbf{0} & \mathbf{X}_{t_2} & \cdots & \mathbf{0} \\ \vdots & \vdots & \ddots & \vdots \\ \mathbf{0} & \mathbf{0} & \cdots & \mathbf{X}_{t_6} \end{bmatrix} \begin{bmatrix} \beta_{t_1} \\ \beta_{t_2} \\ \vdots \\ \beta_{t_6} \end{bmatrix} + \begin{bmatrix} \gamma_{t_1} & 0 & \cdots & 0 \\ 0 & \gamma_{t_2} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & \gamma_{t_6} \end{bmatrix} \begin{bmatrix} \mathbf{q}^{T} \\ \mathbf{q}^{T} \\ \vdots \\ \mathbf{q}^{T} \end{bmatrix} + \begin{bmatrix} \varepsilon_{t_1} \\ \varepsilon_{t_2} \\ \vdots \\ \varepsilon_{t_6} \end{bmatrix} \qquad (5.20)$$

and can be solved through the use of maximum likelihood estimation.

Empirical Model

I again expect that the demand for emission reductions given in equation (5.4) is a good explanation of the European nations' behavior during the 1980's with regards to SO_2 and NO_x reductions. However, more observations on the explanatory and dependent variables will be needed than in the "snapshot" models of the previous chapter in order to test this hypothesis and construct an econometric model.

In my model the β_{t_i} will have different numbers of explanatory variables since the date the Helsinki and Sofia Protocols went into force adds an emissions target variable (for the sulfur model), and a variable indicating protocol ratification (similar to the variables added to the post-Helsinki and post-Sofia models in chapter 4). With the exception of the dependent variable and the cost of emission reductions variable, the variables in the spatial SUR model are the same as those used in the earlier spatial autoregressive models, but cover more time periods.

Variable Definitions

Measures of q_{it}^{v} and q_i^T

Yearly emissions of SO_2 and NO_x are again from Tuovinen et al., 1994. The target level of reductions, q_i^T, is calculated in the same way as before. Under the Helsinki Protocol it is 0.3 × S80 (30% of 1980 sulfur emissions), but there is no target for NO_x emissions. Voluntary emission reductions for sulfur are calculated as follows: for the 1980-85 period they consist of the difference between the 1980 emissions and the 1985 emissions, S80 – S85, and for the other periods they are the emission target level minus that year's emissions, i.e. $q_{it}^{v} = 0.7 \times S80 - SYY$ (where YY = time period t)). Voluntary reductions for NO_x are calculated by subtracting current year emissions from previous year emissions (except for the 1980-85 period where it is N80 – N85). Then a two-year moving average is taken of these values because the results of the regressions using the raw reduction data were unstable from one time period to the next.

Measures of p_{it}

The cost of emission reductions is proxied by per capita consumption of fossil fuels because there is a possibility of an endogeneity problem over a several year period since the amount of emission reductions may influence the cost of emission reductions. For sulfur, I use the per capita consumption of solid, liquid, and gaseous fossil fuels, PCC-FUEL, and for NO_x, I use the per capita consumption of liquid fossil fuels, PCC-LIQ. This data comes from the 1979 and 1988 United Nations' Yearbook of World Energy Statistics, which is published each year. PCC-FUEL is used in place of MCSUL and PCC-LIQ is used instead of MCNOX, used in the previous chapter.

Measures of m_i, α_{ii}, $\tilde{Q}_{it}$, E_i

These explanatory variables come from the same sources as those used in the previous chapter. However, consecutive years will be used for some of the variables.[2] Tables 5.3 and 5.4 summarize the dates of the explanatory variables for each time period used in the Sulfur and NO_x models.

---

[2] Additional data for FREE comes from McColm (1991).

Table 5.3. Dates of the Explanatory Variables for the Sulfur Regression

Sulfur Variables	1980-85	1986	1987	1988	1989	1990
SPILL	1980-85	1986	1987	1988	1989	1990
GDP	1983	1985	1986	1987	1988	1989
FREE	1983	1985	1986	1987	1988	1989
OWNSUL	1985	1985	1985	1985	1985	1985
PCC-FUEL	1985	1985	1987	1988	1989	1990
TARGET	1980	1980	1980	1980	1980	1980
HELSINKI	none	none	1986	1987	1988	1989
URBAN	1985	1985	1985	1990	1990	1990
PFOREST	1985	1985	1985	1985	1985	1985

Table 5.4. Dates of the Explanatory Variables for the NO_x Regression

NO_x Variables	1980-85	1980-86	1986-87	1987-88	1988-89	1989-90
SPILL	1980-85	1980-86	1986-87	1987-88	1988-89	1989-90
GDP	1983	1985	1986	1987	1988	1989
FREE	1983	1986	1987	1988	1989	1990
OWNSUL	1985	1985	1985	1985	1985	1985
PCC-LIQ	1980	1985	1987	1988	1989	1990
SOFIA	none	none	none	none	1989	1990
URBAN	1985	1985	1985	1990	1990	1990
PFOREST	1985	1985	1985	1985	1985	1985

Empirical Results

Sulfur

Table 5.5 displays the results of the sulfur regressions. Four of the five post-Helsinki results (1986-90) confirm the subscription model. The coefficients on the SPILL terms indicate that for every 1 kiloton (kt) decrease in voluntary regional emission spillins to a nation,[3] that nation, on average, decreased its voluntary emission reductions of sulfur (SO_2) by 210 tons in the 1987 period, by 540 tons in the 1989 period, and by 760 tons in the 1990 period.

Each year that passes appears to have increased the degree of free-riding among nations, since the SPILL coefficient is becoming increasingly negative. The estimated coefficient for the 1989 SPILL term is significantly more negative than the 1988 SPILL term and is significantly less negative than the 1990 SPILL term. It appears that as time passed, the European countries engaged in more free-riding behavior. In other words, strategic behavior and free-riding increased in the years following the signing of the 1985 Helsinki Protocol. This conclusion runs counter to the general view that international treaties governing air pollution are a sign that nations are cooperating with each other. Unfortunately, no firm conclusions can be formed about behavior before the signing of the protocol since the coefficient is not significant for the 1980-85 period.

---

[3] The terminology is awkward because the dependent variable is voluntary emission reductions, but the a_{ij} which are used in calculating the SPILL coefficient are based on total depositions in the 25 nations.

Table 5.5. Maximum Likelihood Estimates of the Spatial SUR Model for SO_2 Emission Reductions (Z-values in Parenthesis)

	1980-85	1986	1987	1988	1989	1990
SPILL	0.01	-0.07	-0.21	-0.23	-0.54	-0.76
	(0.10)	(-0.91)	(-2.82)	(-2.18)	(-5.82)	(-5.56)
GDP	0.99	1.23	1.34	1.77	1.87	1.40
	(2.85)	(3.37)	(3.97)	(4.38)	(5.27)	(4.72)
PCC-FUEL	-0.10	-0.10	-0.10	-0.11	-0.07	-0.03
	(-4.75)	(-5.06)	(-5.31)	(-5.20)	(-3.96)	(-1.32)
OWNSUL	15.03	11.77	16.97	7.31	10.61	23.03
	(0.76)	(0.56)	(0.89)	(0.36)	(0.60)	(1.61)
FREE	50.04	48.83	57.31	41.99	49.56	54.69
	(3.17)	(2.96)	(3.85)	(2.51)	(3.18)	(3.76)
TARGET		-0.98	-1.02	-1.07	-1.08	-0.81
		(-11.45)	(-9.83)	(-5.60)	(-6.03)	(-4.68)
HELSINKI			54.87	78.37	112.51	205.46
			(5.71)	(2.61)	(3.17)	(2.93)
URBAN	4.73	2.55	2.53	4.94	2.10	0.54
	(1.43)	(0.82)	(1.24)	(2.90)	(1.14)	(0.19)
PFOREST	-0.91	0.89	0.02	3.27	3.24	-0.30
	(-0.13)	(0.11)	(0.00)	(0.44)	(0.46)	(-0.06)
CONSTANT	174.27	312.84	199.01	154.49	120.72	-232.97
	(0.41)	(0.74)	(0.54)	(0.41)	(0.40)	(-0.73)
-Log Likelihood	887.03	887.03	887.03	887.03	887.03	887.03
R^2	0.73	0.73	0.73	0.73	0.73	0.73

Notes: Only one Maximum Likelihood Estimate and one R^2 is reported for the model, because a spatial SUR regression does not generate separate MLEs and R^2s for each time period.

GDP is positive, significant and is increasing each year, except the 1990 period, but the increases are not statistically significant from one year to the next. However, comparing periods over several years does show significant changes. The 1988 and 1989 periods have GDP that is significantly higher than the 1980-85 and 1986 periods. This implies that the contribution of GDP to SO_2 emission reductions increased over the decade. In the 1980-85 period, every $1 billion increase in GDP resulted, on average, in a reduction of 990 kilotons of SO_2 emissions. Four years later, in the 1989 period, the contribution of GDP almost doubled. In that period every $1 billion increase resulted in 1,870 kilotons of voluntary reductions of SO_2 emissions.

It is a bit more difficult to tell a story about the roll of the cost of emission reductions for SO_2. PCC-FUEL is negative and significant in five of the six periods, but none of them are significantly different from each other. Ceteris paribus, a 1% increase in the amount of fossil fuel used per capita, resulted in a 100 ton decrease in emissions reductions during the first three periods (1980-85, 1986, and 1987), a 110 ton decrease in the 1988 period, and a 70 ton decrease in the 1989 period. Over the 1980's then, it appears that the "cost" of emission reduction played a stable role in determining a nation's level of voluntary emission reductions.

OWNSUL is positive as expected for all periods but only marginally significant in the last period (1990). The value of the coefficients are all of the same magnitude averaging between 7 and 17 kt (except in 1990). A tentative hypothesis then would be that the percentage of a nation's emissions landing on itself played a marginally positive role in reducing emissions.

FREE is positive and significant in all periods. On average, a free country reduced its SO_2 emissions between 42 and 55 kt more than a non-free country for each one unit increase in its civil and political liberties. Therefore, the most free countries (those with values of 2) had regional emissions 300 kt less, on average, than non-free countries (values of 8).[4] There is no significant difference in the coefficients during the period under study, so it appears that political and civil liberties played a relatively constant role in influencing a nation's SO_2 emission reductions during the 1980's.

Likewise, the nation's required level of SO_2 emissions for 1993, TARGET, is significant in all periods but displays no significant difference between periods. Ceteris paribus, a one kt increase in TARGET resulted in decreases of voluntary emissions of between 0.81 and 1.08 kt. With the exception of the 1986 period and the 1990 period, the mandated target decreased voluntary reductions by more than one-to-one. But none of the estimated coefficients are significantly different from one. Surprisingly, there is no significant difference in the European nations' behavior regarding their target emission levels over time. One would expect that the closer a nation came to achieving its target level, the more likely it would be to make more voluntary reductions. Therefore I expected to see the coefficient for TARGET become less negative in each time period.

---

[4] Since FREE takes on a value between 2 (most free) and 14 (most unfree), The nations with a value of 2 contributed about 100 kt (50 kt × 2) to sulfur emissions while a nation with a rating of 8 would contribute about 400 kt (50 kt × 8) to sulfur emissions. Therefore, 300 kt is the difference between the two.

Instead, there was a gradual increase in the negative value up until the 1990 period, when the coefficient suddenly dropped to -0.81 (the largest change of any time period). However, no definite conclusion can be drawn from this drop, because the change in value was not quite significant. On the other hand, the drop in the *Z* values from -11.45 in the 1986 period to -4.68 in the 1990 period indicates that there is more variation in voluntary reductions due to the influence of TARGET in the later periods. This could mean that some of the nations are behaving as one would expect as the target level is approached.

The ratification of the Helsinki Protocol made a country much more likely to reduce its voluntary emissions. Also the earlier a nation ratified the Helsinki Protocol, the more likely it was to make voluntary SO_2 emission reductions. Interestingly, the voluntary reductions in the first year after a nation ratified the protocol were greater for nations that joined later. This is shown because the coefficients increase over time and are significantly different from each other in three of the four periods. Nations that ratified the protocol in the year following its adoption (1987) made voluntary reductions 54.87 kt greater, on average, than nations that did not ratify that year. But in the 1990 period, nations that ratified the protocol, made voluntary reductions 205.46 kt greater than those that had still not ratified the treaty. However, it is important to note that a nation that had ratified the protocol three years previously (1987) was now making voluntary reductions of 821.84 kt more than the non-ratifying nations and 616.38 kt more than nations that ratified it that year.[5]

---

[5] HELSINKI is an integer variable that changes from 0 to 1 when a nation ratifies the protocol and then increases by one for each year that follows. Therefore a nation that ratified the Helsinki Protocol in the

While health and environmental effects are theoretically appropriate in determining a nation's level of emission reductions, the proxy variables, PFOREST and URBAN do not appear to have significant explanatory power. As predicted, URBAN is positive in all periods but is significant in only the 1988 period. While not much importance should be attached to one significant time period, the interpretation of it is straight forward. A one percent increase in a country's urbanized population resulted in a 4.94 kt increase in voluntary emission reductions of SO_2. But PFOREST is not significant in any of the periods. Therefore, it appears that during the 1980's, nations did not significantly take into account the effect of SO_2 emission reductions on their forests or urbanized populations. In order to obtain more evidence for the above conclusion, another model was run without URBAN and PFOREST. Using the results (unreported) of this model and the results of the reported model, I calculate two tests appropriate for nonlinear regressions. The first is the Asymptotically Valid *F* Test which is used to test whether the inclusion of PFOREST and URBAN significantly improved the fit of the model. The resulting $F_{[12, 93]}$ gave a value of 0.76 which was well below the 95-percent critical value of 1.86. Therefore, the hypothesis that there is not a significant difference between the models cannot be rejected. The *F* distribution is only approximate because neither the numerator nor denominator posses the necessary chi-square distribution since the models are nonlinear. The second test, the Likelihood Ratio Test, gave a similar result with a

---

1987 period has a value of 4 in the 1989-90 period. Therefore the calculations were as follows: 821.84 = (4 × 205.46) and 616.38 = (821.84 - 205.46).

value below the 90-percent critical value (18.55) of the chi-square distribution with 12 degrees of freedom (i.e. 12 restrictions -- 2 variables covering 6 time periods).[6]

Nitrogen

As in the previous chapter, the NO_x model offers less support for the theoretical model than the sulfur model (the results are reported in Table 5.6). Because the results of the regressions for one-year periods varied so much, I used two year moving averages of the available emissions data. Six periods resulted: 1980-85, 1980-86, 1986-87, 1987-88, 1988-89, and 1989-90.

The 1988-89 time period is substantially different from the periods coming before and after it, so I am reluctant to draw any conclusions using it. The coefficients for GDP, OWNNOX, and PFOREST were significant in the 1987-88 and 1989-90 periods but not significant in the 1988-89 period. Conversely, FREE was not significant in either of those periods but was significant in the 1988-89 period. Furthermore, URBAN also displayed unusual behavior in this period when comparing it with the previous period.

There are no significant political or economic events that occurred during this period that would explain the difference in the estimated coefficients for only the NO_x regression. The European economy was slowing down during this period because GDP, in the countries under study, declined (on average) from 3.6% in the 1987-88 period to 3.0% in the 1988-89 period. It fell even further in the 1989-90 period to 2.3%. Therefore

---

[6] The maximum likelihood estimate of the regression without URBAN and PFOREST was -893. So $\lambda = -2(-893 - (-887)) = 12$.

Table 5.6. Maximum Likelihood Estimates of the Spatial SUR Model for NO$_x$ Emission Reductions (Z-values in Parenthesis)

	1980-85	1980-86	1986-87	1987-88	1988-89	1989-90
SPILL	-0.51	-0.53	-0.49	-1.00	-0.98	-0.41
	(-4.59)	(-4.78)	(-4.38)	(-7.40)	(-3.95)	(-1.84)
GDP	0.02	0.04	0.05	0.92	0.05	0.18
	(0.49)	(2.15)	(3.89)	(9.78)	(0.37)	(2.36)
PCC-LIQ	0.001	(0.001)	0.000	0.015	-0.030	-0.012
	(2.69)	(1.11)	(0.01)	(3.82)	(-0.97)	(-0.78)
OWNNOX	-3.25	-8.02	-10.37	-12.89	-0.26	-12.05
	(-1.17)	(-6.02)	(-9.71)	(-7.68)	(-0.04)	(-2.82)
FREE	1.79	1.44	1.26	0.32	12.28	4.65
	(3.61)	(4.17)	(3.41)	(0.36)	(2.95)	(1.12)
SOFIA					-24.90	-19.22
					(-0.81)	(-1.11)
URBAN	0.90	0.11	-0.29	-0.77	2.69	1.49
	(0.76)	(0.24)	(-1.54)	(-2.75)	(1.40)	(1.30)
PFOREST	0.66	1.28	1.60	1.97	1.32	2.53
	(0.49)	(1.97)	(2.85)	(2.23)	(0.64)	(2.00)
CONSTANT	-52.19	-4.14	19.87	31.11	-162.05	-64.01
	(-0.56)	(-0.11)	(0.89)	(0.89)	-1.10	-0.71
-Log Likelihood	648.00	648.00	648.00	648.00	648.00	648.00
R^2	0.37	0.37	0.37	0.37	0.37	0.37

Notes: Only one Maximum Likelihood Estimate and one R^2 is reported for the model, because a spatial SUR regression does not generate separate MLEs and R^2s for each time period.

neither economic growth nor decline appear to explain the differences among the coefficients over the time periods in question.

The SPILL terms are all negative and significant in each period, implying that free-riding also occurs with NO_x emission reductions. Between 1980 and 1987 a nation appears to have increased its emissions about 500 tons for every 1000 tons of reduced NO_x depositions that fell on its soil. This free-riding doubled in the 1987-88 and 1988-89 periods as nations increased their own voluntary emissions of NO_x by 1 ton for every ton of reduced spillins. However, in the last period (1989-90), the free-riding appeared to fall back to around its old level with each nation increasing its emissions 410 tons for each kiloton decrease in voluntary spillins.

There is a significant difference in the coefficients of three groups: the 1980-87 group, the 1987-89 group, and the 1989-90 period. It appears that shortly before the Sofia treaty came into force (1988), nations began to behave less cooperatively than they had in the 1980-86 period, but then returned to their old pattern of behavior in the 1989-90 period. I can think of no obvious explanation for this behavior.

GDP tells a story somewhat different story from the simple model of chapter 4. Here two of the three pre-Sofia coefficients for GDP are positive and significant, as is GDP in the post-Sofia period (1989-90). In the two periods between 1980 and 1987, every $1 billion increase in GDP resulted in between a 40 and 50 ton increase in NO_x emission reductions. However, in the 1989-90 period a $1 billion increase in GDP, ceteris paribus, resulted in a three times greater increase (180 tons) in emission reductions. This is a significant increase over the 1980-86 and 1986-87 periods but significantly under the 1987-88 period. A tentative conclusion drawn from these results is that GDP does appear to play a significant positive role in NO_x emission reductions during the period of study but it cannot be determined whether this role is increasing in magnitude as it did in the case of SO_2 emission reductions.

PCC-LIQ is positive but near zero in the first three periods, but in the last two periods it becomes negative, although not significant. The per capita consumption of liquid fossil fuels was used as a proxy variable for the cost of reducing NO_x emissions, but the results are similar to those of the simple models in the last chapter which used actual marginal costs of emission reduction. The coefficients were positive but not consistently significant in the pre-Sofia periods but became negative, though not significant in the post-Sofia periods. Therefore, I come to the same conclusion as I did in the last chapter: it appears, that cost was not a consistently important factor in decisions of NO_x emission reductions during the period under study. However there are subtle hints that cost is beginning to be taken into account.

OWNNOX is negative in all periods but there does not appear to be a consistent pattern to the results. I had hoped that this new model would help explain the unexpected OWNNOX results from the last chapter, but the puzzle still remains because these new results are similar to the old results, showing negative values which are sometimes significant and sometimes not. I therefore feel that no conclusion can be drawn about the relationship between the amount of NO_x depositions and the European nations' decision to reduce NO_x emissions.

Political and civil liberties, indicated by FREE, had a positive and significant influence on emission reductions in four of the six periods under study. This gives support to the belief that environmental quality (indicated by both reductions in sulfur and NO_x emissions) is responsive to the degree of political freedom of a nation's citizens. In the 1986-87 period, the most free nations made emission reductions that were more than 7,560 tons greater than the non-free nations.[7] But there is no clear pattern of change in the coefficients' values over time. The pre-Sofia periods give consistent estimates for FREE but in the post-Sofia period, the results break down, giving an insignificant value followed by a large significant value, then by another insignificant value. These results can be contrasted to the results of the previous chapter, in which the FREE coefficients were negative but marginally significant in the pre-Sofia period, but then followed by positive but not significant values in the post-Sofia period. Therefore I am again reluctant to draw any conclusions beyond my belief that this model presents evidence that NO_x emission reductions are more likely in countries with stronger civil and political liberties.

The proxy variables for environmental and health effects of emission reductions (PFOREST and URBAN) displayed mixed results. While, URBAN displayed both positive and negative values, PFOREST performed better. It was positive in all periods,

---

[7] The FREE variable is the same as that used in the sulfur models with a value that ranges between 2 and 14. The freest nation contributed 2.52 kt (1.26 × 2) of NO_x in the 1986-87 period, while a nation with a rating of 8, contributed 10.08 kt (1.26 × 8) of NO_x (7.56 = 10.08 - 2.52).

and significant in four of the six periods. Ceteris paribus, each 1% increase in the land area classified as forest resulted in an extra 1.6 kt decrease in NO_x emissions in the 1986-87 period and a 2.53 kt decrease in the 1989-90 period. It appears that, at least for NO_x depositions, nations were cognizant of the possible damages their forests might experience and took that into consideration when making decisions on emission reductions.

This result is different than the sulfur model, in which it appeared that urbanization rather than the percentage of forest, played a role in determining a nation's SO_2 emission reduction decisions. The difference is somewhat surprising because NO_x is a major component of ozone, a common problem in cities, while the damage done to forests by acid rain and sulfur is better understood than the effects of nitrogen, which is also a plant fertilizer.

The Likelihood Ratio Test gives confirmation of the usefulness of including PFOREST in the model. Without PFOREST, the MLE was -655; with it, the MLE increased to -648.00.[8] Given six restrictions (one variable in six time periods) the Log Likelihood Test resulted in a value of 14 which is greater than the 95-percent critical value of the chi-square distribution of 12.59. Thus, there is a significant reason to reject the hypothesis that the models with and without PFOREST are identical. In addition, the inclusion of both PFOREST and URBAN resulted in a marginally better fitting regression. According to the Likelihood Ratio Test, I calculated a value of 18.88 which exceeded the 90-percent critical value of 18.55.

---

[8] Neither of the models that generated these estimates are reported.

Conclusion

The explanatory power of the sulfur model was almost twice as good as that of the NO_x model. The sulfur model explained almost three fourths of the variation in SO_2 emission reductions, according to the R^2, while the NO_x model explained only 37%. Likewise, many of the estimated coefficients in the sulfur model were significant, but in the NO_x model, there was a much smaller number of significant coefficients. Thus, many of my earlier questions can only be answered with reference to the sulfur model and some doubt remains if the answers are also correct in regards to the NO_x model.

Strategic or noncooperative behavior was apparent in both models as shown by the negative and significant values of the SPILL terms. In the sulfur model, the strategic behavior became more pronounced each year, even after the signing of the Helsinki Protocol. This indicates that free-riding off others voluntary SO_2 emission reductions was common and growing stronger among the European countries in spite of treaties and protocols. Future treaties and protocols should take this into account when they are written so that the free-riding will be lessened. This could possibly be done by mandating higher individual target levels of reductions for each nation, so that there are few voluntary emissions for a nation to free-ride on.

Income transfers among nations may also help to achieve a cleaner and healthier atmosphere because in both the sulfur and NO_x models, GDP was positively associated with emission reductions. This effect was clearer, stronger, and generally increasing over time in the sulfur model but also positive and usually significant in the NO_x model. Future treaties that provide some incentive based system for emission reductions in the poorer countries may be able to achieve lower emissions at reduced cost. This will be especially true in the case of sulfur emissions which appear to be more strongly influenced by a nation's GDP.

Encouraging movement away from fossil fuels should lower SO_2 emission levels among the European countries according to the sulfur model. Naturally, this conclusion reinforces what is already well-known. And the same can be said for liquid fossil fuels, since they are the predominant source of NO_x depositions. Strangely, this obvious conclusion was not borne out by the results of the NO_x model. Showing once again, that the unitary actor assumption of both models may not be so good at describing a nation's actions in regards to NO_x emissions.

The increase in political liberty that the citizens of the former communist bloc nations experienced beginning in 1989 bodes well for both SO_2 and NO_x emission reductions. The models indicate that SO_2 emissions should fall the most in those countries that have become more democratic, but there should also be a fall in the NO_x emissions as well. Since this study ends at the time when the democratic transition began, I am interested in finding out if future studies can confirm this hypothesis.

If future emission control treaties reward nations that join early, it may result in greater amounts of emission reductions over the following years. This will be especially likely to occur in regards to SO_2 emissions, where the regression results show that early ratifiers of the Helsinki Protocol are more likely to make substantial reductions than the later ratifiers. The same conclusion cannot be drawn in regards to NO_x emission reductions, but that is not surprising as there were fewer periods of post-protocol behavior to examine.

Perhaps the most important factor for future treaty writers to consider is the use of mandated emission reduction levels. While no firm conclusions can be drawn concerning the NO_x model because of the late date of the treaty, the sulfur model indicates that emission targets may result in nations making a greater than one for one trade off in their mandated versus their voluntary emission levels. Furthermore, this effect did not diminish with the passage of time. If this conclusion holds true until the target date is reached, the result may be counter-intuitive. Namely, a treaty with mandated emission levels may achieve less emission reductions than a treaty that does not mandate set levels.

The variables that are proxies for environmental and health concerns (PFOREST and URBAN) did not give consistently significant results. But a tentative conclusion is worth stating. It appears that forest cover exerted a stronger influence on NO_x emission reductions than did urbanization but the reverse was true for SO_2 emissions. This result is surprising because it is the reverse of what one expects based on current scientific knowledge of the chief recipients of the damage caused by NO_x and sulfur depositions, cities and forests respectively. This tentative result needs further study to find out if it is true, and if so, whether nations are not taking current scientific knowledge into account, or whether there are other unknown reasons for their behavior.

Finally, it is again clear, as it was in the last chapter, that the theoretical model explains SO_2 emission reductions much better than NO_x emission reductions. The reason is most likely because the assumption of a unitary decision maker is not appropriate in the case of NO_x emissions because NO_x emissions come mainly from cars while SO_2 comes mainly from large power plants. Thus another theoretical model appropriate for non-unitary decision makers needs to be developed and tested to see if NO_x emission can be better explained.

CHAPTER 6. CONCLUSION

This chapter first summarizes the theoretical and empirical findings of my dissertation and analyzes how these findings contribute to an understanding of the Helsinki and Sofia Protocols. Second, the relevancy of these findings to the theoretical and empirical work in public goods, in general, and to models of impure public goods, in particular, will be discussed. Third, future research areas the dissertation points toward will be examined.

Summary

Chapter 3 showed that impure public goods problems differ based on the good's public supply technology. In addition, the effect of differing spatial weight matrices (determined by the amount of private and public benefits of the good) was shown to be important in determining the pattern of payoffs in coordination games. This chapter also showed how the number of required participants, the degree of certainty, and the pattern of payoffs determined the outcome of coordination games among small groups and how this knowledge was relevant in understanding the current transnational problems of stratospheric ozone depletion, global warming, acid rain, and tropical deforestation.

Chapter 4 developed a theoretical model, based on both Nash subscription and oligarchy choice, then empirically tested the model using spatial autoregression (with nonsymmetric spatial weight matrices) for SO_2 and NO_x emission reduction data from 25

European nations. The results indicated that the nations exhibited strategic behavior for both SO_2 and NO_x emission reductions before and after the signing of the Sofia and Helsinki Protocols. The sulfur model fitted the data best and showed that GDP, political freedom, treaty ratification, and the percentage of emissions falling back on a nation's own soil had positive and significant influences on voluntary emission reductions, while the target level of emission reductions had a negative influence on voluntary SO_2 reductions. However, marginal cost and proxy variables for the environment and human health did not play significant roles.

A more advanced spatial SUR model was used in chapter 5. This model used yearly data rather than simply pre- and post-treaty data and allowed changes in the variables to be tracked over time. The empirical results supported the findings of chapter four and showed that strategic behavior occurred in every year before and after the protocols took effect. The results showed that nations decreased their reductions of NO_x and SO_2 in response to decreased depositions of these pollutants on their own soil from neighboring countries. This strategic behavior appeared to be increasing each year, with regards to voluntary reductions of SO_2, thus implying an absence of a cooperative response.

GDP and political freedom performed as predicted in both models. Increased levels of GDP were positively associated with voluntary emission reductions of SO_2 and NO_x, and this effect was increasing over time in the sulfur model. Likewise, countries with greater civil liberties and political freedoms typically made greater voluntary emission cutbacks compared with nations that had less freedom and civil liberties, but this result was again more pronounced and significant in the sulfur model than the NO_x model.

The sulfur and NO_x models also differed in the significance attached to the estimated coefficients for treaty ratification and the proxy for the cost of emission reductions. In the case of the sulfur model, the estimated coefficient for cost was negative and significant, but it was positive and significant for treaty ratification. In contrast, the results for these variables in the NO_x model were not significant. Another difference was found between the estimates of variables for human health and the environment. Urbanization was more closely associated with reductions in SO_2, while the percentage of a nation's land classified as forest appeared to have a more positive and significant effect in determining voluntary reductions of NO_x.

Therefore, the empirical results again showed that SO_2 emission reductions were better explained by the theoretical model than were NO_x emission reductions. One reason may be the number and sources of emissions. There are a few large emission sources for SO_2, making them easier to control and monitor than NO_x emissions which come from many small sources (vehicles). The second reason may be that both models were based on the assumption of unitary actors. Although sulfur emission reductions appear to follow that assumption, nitrogen emission reductions do not, because legislation reducing NO_x emissions does not usually apply to the majority of emission sources (such as older cars and trucks).

Analysis of the Helsinki and Sofia Protocols

My findings cast doubt on the belief that the Helsinki and Sofia Protocols led to true cooperation among nations. In chapter 3 I demonstrated that cooperation was unlikely to occur in large groups (such as the 25 nations under study) when efforts must be coordinated and there is uncertainty about the benefits arising from the coordinated effort (as is the case with SO_2 and NO_x emissions reductions). The results of chapter 3 and four gave support for this conclusion, because the coefficient, SPILL, was negative for both sulfur and NO_x models indicating that nations were benefiting from the emission reductions from other nations ("spillins") and "easy-riding" by cutting back on their own emission reductions. This strategic, or noncooperative behavior, increased over time and was quite noticeable after the Helsinki Protocol took effect.

The amount of Nash behavior displayed by the European nations runs counter to the general impression of the goals of emission treaties. In both sulfur and NO_x models, nations appeared to behave in a more strategic way. There was a clear pattern in the sulfur model, but it was also apparent to a smaller degree in the NO_x models. Also the SPILL term in the sulfur model appeared to show that the Nash behavior became stronger and more significant over time, as if nations began to learn how increased spillins made their emission reductions less necessary.

The cooperative solution will be difficult to achieve without additional incentives, because a neighbor's emission reductions are a good substitute for one's own emission reductions. Thus, side payments, cultural exchanges, or other treaties will be necessary for nations to coordinate their emission reduction efforts and reduce or eliminate their non-cooperative behavior. If however, emission reductions come to be regarded as complements to other desirable commodities or activities, then non-cooperative behavior would also be reduced.

The knowledge gained from the empirical and theoretical results is directly applicable to future treaty formation. Future emission treaties should take into account the number of nations, the uncertainty of the benefits of pollution reduction, the relevant spatial weight matrices, the technology of public supply, the transactions costs, and the number and sources of the emissions. The Helsinki and Sofia Protocols appeared to have taken differences in the pollutants into account when the targets were set but did not take into account differences between nations because every nation was required to meet the same standard. Future pollution control treaties will come closer to achieving a least-cost cooperative solution if emission reduction targets are set based on differences in both spillins among nations and in emission reduction costs. The Oslo Protocol of 1994 has taken differences among nations into account because the mandated emission reductions for each nation are no longer the same as they were under the Helsinki and Sofia Protocols.

Additions to Public Goods Theory

When discussing commons problems, traditional public goods theory does not distinguish impure public goods based on the degree of rivalry and excludability of the good, nor the good's technology of public supply. This dissertation has shown that such distinctions are necessary for both empirical and theoretical reasons. In addition, game theory can be made more relevant to impure public goods, such as pollution, by using spatial weight matrices which show how the benefits (or costs) of the good are distributed among players. Differing spatial weights affect both equilibrium outcomes, as well as the payoff structure. The payoff structure can also be changed substantially when the spatial weight matrix is nonsymmetric, as it is for many types of pollutants. Finally, it was shown that the technology of public supply adds an additional dimension to game theory and public goods problems.

On the empirical side, spatial econometrics offers an alternative to traditional public good models because the use of spatial weight matrices allows economists to examine a wider variety of public goods' problems. Non-symmetric spatial weight matrices allow questions dealing with air and water pollution to be examined, because wind directions or the way a river flows can be represented with this type of matrix. The results of this dissertation have shown the importance of using nonsymmetric spatial weights in empirical modeling because they turned out to possess significant explanatory power in determining the European nations' emission reduction decisions.

Future Research

The findings of this study point to several areas for future research. Obviously, the first research objective is the application of the spatial SUR model to the post-1990 period to see if the model's results are consistent with the new data and the new countries, and whether cooperation has increased in this post-treaty period. Secondly, a new theoretical model, possibly built on the median voter model, should be developed to see if it can better explain NO_x emission reductions. Third, the spatial SUR model should be applied to other impure public pollutants such as ammonia and Voluntary Organic Compounds (VOCs). This will show how robust the theoretical model is for explaining other types of emissions. Fourth, a computer simulation using the data and results from my dissertation can be developed to simulate the European nations' emission reductions of transboundary pollutants. This simulation will allow one to determine the effects of different spatial weight matrices and control costs on achieving a stable equilibrium emissions level. These results can then be compared with actual behavior to see how close nations are to reaching an equilibrium. Fifth, the application of spatial econometrics to other impure public goods problems at the national, urban, and regional level is needed. And sixth, the theoretical model should be developed further to incorporate more advanced game theoretic ideas such as signaling, incomplete information, and multi-stage games, because these ideas allow a much more realistic examination of the process of treaty formation and adherence. For example, incomplete information is a more reasonable assumption for transboundary pollutants because the long-term health and environmental effects are still not known with certainty. Multi-stage games also give extra freedom in examining pollution control treaties because nations make reduction decisions in the first stage, before targets have been set. Then, more decisions are made in the stage before the target reduction deadline is reached, and finally, there is a final stage that occurs after the deadline has passed and before the next treaty takes affect. Allowing signaling in the model may help examine the importance of Leader-Follower behavior because some countries serve as the initiators of emission reduction treaties (such as Germany, and the Scandinavian countries) which sends a signal to the other countries about future emission policy that may have some effect (positive or negative) on their emissions' policy.

REFERENCES

Alcamo, Joseph and Elidoro Runca (1986). "Some Technical Dimensions of Transboundary Air Pollution." In Transboundary Air Pollution, eds. Cess Flinterman, Barbara Kwiatkowska and Johan G. Lammers, 1-17. Dordrecht, The Netherlands: Martinus Nijhoff Publishers.

Anselin, Luc (1988). Spatial Econometrics: Methods and Models. Norwell, MA: Kluwer Academic Publishers.

Anselin, Luc and Daniel A. Griffith (1988). "Do Spatial Effects really matter in regression Analysis?" Papers of the Regional Science Association 65, 11-34.

Anselin, Luc and Sheri Hudak (1992). "Spatial Econometrics in Practice; A Review of Software Options." Regional Science and Urban Economics 22, 509-536.

Barrett, Scott (1991). "The Problem of Global Environmental Protection." In Economic Policy Towards the Environment, ed. Dieter Helm, 137-215. Oxford: Blackwell.

______ (1992) "Self-Enforcing International Environmental Agreements." Mimeo, Centre for Social and Economic Research on the Global Environment, London: London Business School.

______ (1993). Convention on Climate Change: Economic Aspects of Negotiations. Paris: Organization for Economic Cooperation and Development.

______ (1994). "Self-Enforcing International Environmental Agreements." Oxford Economic Papers 46 (supplement), 878-894.

Bergstrom, Theodore C., Lawrence Blume, and Hal Varian (1986). "On the Private Provision of Public Goods." Journal of Public Economics 29, 25-49.

Black, Jane, Maurice D. Levi, and David de Meza (1993). "Creating a Good Atmosphere: Minimum Participation for Tackling Greenhouse Effect." Economica 60, 281-93.

Bruce, Neil (1990). "Defense Expenditures by Countries in Allied and Adversarial Relationships." Defence Economics 1, 179-195.

Carraro, Carlo and Domenico Siniscalco (1993). "Strategies for the International Protection of the Environment." Journal of Public Economics 52, 309-328.

Chichilnisky, Graciela and Geoffrey Heal (1993). "Global Environmental Risks." Journal of Economic Perspectives 7, 65-86.

Cleveland, William S. (1993). Visualizing Data. Summit, NJ: Hobart Press.

Cliff, A. D. and J. K. Ord (1975). "Model Building and the Analysis of Spatial Pattern in Human Geography." Journal of the Royal Statistical Society B 37, 297-328.

Congleton, Roger D. (1992). "Political Institutions and Political Control." Review of Economics and Statistics 74, 412-421.

Conybeare, John A. C., James C. Murdoch, and Todd Sandler (1994). "Alternative Collective-Goods Models of Military Alliances: Theory and Empirics." Economic Inquiry 32, 525-542.

Cooper, Russell W., Douglas V. DeJong, Robert Forsythe, and Thomas W. Ross (1990). "Selection Criteria in Coordination Games: Some Experimental Results." American Economic Review 80, 218-33.

Cornes, Richard and Todd Sandler (1984a). "Easy Riders, Joint Production, and Public Goods." Economic Journal 94, 787-792.

______ (1984b). "The Theory of Public Goods: Non-Nash Behavior." Journal of Public Economics 23, 367-379.

______ (1985). "The Simple Analytics of Pure Public Good Provision." Economica 52, 103-116.

______ (1994). "The Comparative Static Properties of the Impure Public Good Model." Journal of Public Economics 54, 403-421.

______ (1996). The Theory of Externalities, Public Goods, and Club Goods, 2nd edition. Cambridge: Cambridge University Press.

Cressie, Noel A. C. (1993). Statistics for Spatial Data, revised edition. New York: John Wiley & Sons.

Dubin, Robin (1988). "Estimation of Regression Coefficients in the Presence of Spatially Autocorrelated Error Terms." Review of Economics and Statistics 70, 466-474.

______ (1992). "Spatial Autocorrelation and Neighborhood Quality." Regional Science and Urban Economics 22, 433-452.

Dudley, Leonard and Claude Montmarquette (1981). "The Demand for Military Expenditures: An International Comparison." Public Choice 37, 5-21.

Eliassen, Anton and Jørgen Saltbones (1983). "Modelling of Long-Range Transport of Sulphur over Europe: A Two-Year Model Run and Some Model Experiments." Atmospheric Environment 17, 1457-1473.

Environmental Protection Agency (1987a). Assessing the Risks of Trace Gases That Can Modify the Stratosphere, 7 volumes. Washington, DC: EPA.

______ (1987b). Regulatory Impact Analysis: Protection of Stratospheric Ozone, 3 volumes. Washington, DC: EPA.

Eyckmans, Johan, Stef Proost, and Erik Schokkaert (1993). "Efficiency and Distribution in Greenhouse Negotiations." Kyklos 46, 363-397.

Farrell, Joseph (1987). "Cheap Talk, Coordination, and Entry." Rand Journal of Economics 18, 34-39.

Gastil, Raymond D. (1989). Freedom in the World: Political Rights and Civil Liberties 1988-1989. New York: Freedom House.

Granger, C. W .J. (1969). "Spatial Data and Time Series Analysis." In Studies in Regional Science, ed. A. J. Scott, 1-24. London: Pion.

Hardin, Garrett (1968). "The Tragedy of the Commons." Science 162, 1243-1248.

Harsanyi, John C. and Reinhard Selten (1988). A General Theory of Equilibrium Selection in Games. Cambridge: MIT Press.

Heckathorn, Douglas D. (1989). "Collective Action and the Second-Order Free-Rider Problem." Rationality and Society 1, 78-100.

Helm, Dieter (ed.) (1991). Economic Policy Towards the Environment. Oxford: Blackwell Publishers.

Herber, B. P. (1991). "The Economic Case for an International Law of the Atmosphere." Environment and Planning C: Government and Policy 9, 417-429.

Hicks, John Richard, Sir (1946). Value and Capital; an Inquiry into Some Fundamental Principles of Economic Theory, 2nd edition. Oxford: Clarendon Press.

Hirshleifer, Jack. (1983). "From Weakest-Link to Best Shot: The Voluntary Provision of Public Goods." Public Choice 41, 371-86.

International Institute for Applied Systems Analysis (IIASA) (1993). RAINS Model, Version 6.1, Computer Program. Laxenburg, Austria: International Institute for Applied Systems Analysis.

Klaassen, G. (1992). Average Cost of Reducing Nitrogen Oxide and Sulfur Oxide Emissions in Europe (Report No. WP-92-050). Laxenburg, Austria: International Institute for Applied Systems Analysis.

Latimer, Douglas A., Hari, K. Iyer, and William C. Malm (1990). "Application of a Differential Mass Balance Model to Attribute Sulfate Haze in the Southwest." In Visible and Fine Particulates, ed. C. V. Mathai, 819-830. Pittsburgh: Air and Waste Management Association.

Mäler, Karl-Göran (1989). "The Acid Rain Game." In Valuation Methods and Policymaking in Environmental Economics, eds. H. Folmer and E. van Ierland, 221-252. Amsterdam: Elsevier.

McColm, R. Bruce (1991). Freedom in the World: Political Rights and Civil Liberties 1990-1991. New York: Freedom House.

McGuire, Martin C. (1990). "Mixed Public-Private Benefit and Public-Good Supply with Application to the NATO Alliance." Defence Economics 1, 17-35.

McGuire, Martin C., and Carl H. Groth (1985). A Method for Identifying the Public Good Allocation Process within a group." Quarterly Journal of Economics 100 (supplement), 915-934.

Morrisette, Peter M., Joel Darmstadter, Andrew J. Plantinga, and Michael A. Toman (1990). "Lessons from Other International Agreements for a Global CO_2 Accord." Discussion Paper ENR91-02. Washington, DC: Resources for the Future.

Murdoch, James C., Morteza Rahmatian, and Mark Thayer (1993). "A Spatially Autoregressive Median Voter Model of Recreation Expenditures." Public Finance Quarterly 21, 334-350.

Murdoch, James C. and Todd Sandler (1982). "A Theoretical and Empirical Analysis of NATO." Journal of Conflict Resolution 26, 237-263.

______ (1997a). "Voluntary Cutbacks and Pre-Treaty Behavior: The Helsinki Protocol and Sulfur Emissions." Public Finance Review 25, 139-162.

______ (1997b). "The Voluntary Provision of a Pure Public Good: The Case of Reduced CFCs Emission and the Montreal Protocol." Journal of Public Economics 63, 331-349.

Murdoch, James C., Todd Sandler and Laurna Hansen (1991). "An Econometric Technique for Comparing Median Voter and Oligarchy Choice Models of Collective Action: The Case of the NATO Alliance." The Review of Economics and Statistics 73, 624-631.

Murdoch, James C., Todd Sandler, and Keith Sargent (1994). "A Tale of Two Collectives: Sulfur versus Nitrogen Oxides Emission Reduction in Europe." Institute for Policy Reform Working Paper, No. IPR 98. Institute for Policy Reform, Washington, D.C.

______ (1997). "A Tale of Two Collectives: Sulphur versus Nitrogen Oxides Emission Reduction in Europe." Economica 64, (forthcoming).

National Bureau of Economic Research (1995). "Penn World Tables Mark V." <http://nber.harvard.edu> (Accessed July 1995).

Newspaper Enterprise Association, Inc. (1984). The World Almanac and Book of Facts 1985. Malwah, N. J.: Funk & Wagnalls.

______(1989). The World Almanac and Book of Facts 1990. Malwah, N. J.: Funk & Wagnalls.

Nordhaus, William D. (1991). "A Sketch of the Economics of the Greenhouse Effect." American Economic Review Papers and Proceedings 81, 146-50.

Olson, Mancur (1965). The Logic of Collective Action. Cambridge, MA: Harvard University Press.

______(1993). "Dictatorship, Democracy, and Development." American Political Science Review 87, 567-576.

Olson, Mancur and Richard Zeckhauser (1966). "An Economic Theory of Alliances." Review of Economics and Statistics 48, 266-279.

Organization for Economic Cooperation and Development (OECD) (1990). Control Strategies for Photochemical Oxidants Across Europe. Paris: OECD.

______ (1993). OECD Environmental Data Compendium. Paris: OECD.

Pigou, A. C. (1946). The Economics of Welfare, 4th Edition. London: Macmillan and Company.

Poterba, James M. (1993). "Global Warming Policy: A Public Finance Perspective." Journal of Economic Perspectives 7, 47-63.

Runge, C. Ford (1984). "Institutions and the Free Rider: The Assurance Problem in Collective Action." Journal of Politics 46, 154-81.

______ (1990). "Common Property Resources in a Global Context." Staff Paper P90-27. University of Minnesota, St. Paul: Center for International Food and Agricultural Policy.

______ (1993). "International Public Goods, Export Subsidies, and the Harmonization of Environmental Regulations." In The Environment, Government Policies, and International Trade: A Proceedings, eds. Mathew D. Shane and Harald von Witzke. Washington, DC: Economic Research Service, U. S. Department of Agriculture.

______ (1994). Freer Trade, Protected Environment: Balancing Trade Liberalization and Environmental Interests. New York: Council on Foreign Relations Press.

Samuelson, Paul A. (1954). "The Pure Theory of Public Expenditure." Review of Economics and Statistics 36, 387-389.

______ (1955). "A Diagrammatic Exposition of a Theory of Public Expenditure." Review of Economics and Statistics 37, 350-356.

Sandler, Todd (1992). Collective Action: Theory and Applications. Ann Arbor: University of Michigan Press.

______ (1993). "Tropical Deforestation: Markets and Market Failures." Land Economics 69, 225-233.

Sandler, Todd and A. J. Culyer (1982). "Joint Products and Multijurisdictional Spillovers." The Quarterly Journal of Economics 98, 707-716.

Sandler, Todd and John F. Forbes (1980). "Burden Sharing, Strategy, and the Design of NATO." Economic Inquiry 18, 425-444.

Sandler, Todd and James C. Murdoch (1990). "Nash-Cournot or Lindahl Behavior?: An Empirical Test for the NATO Allies." The Quarterly Journal of Economics 105, 875-894.

Sandler, Todd and John Posnett (1991). "The Private Provision of Public Goods: A Perspective on Neutrality." Public Finance Quarterly 19, 22-42.

Sandler, Todd and Keith Sargent (1995). "Management of Transnational Commons: Coordination, Publicness, and Treaty Formation." Land Economics 71, 145-162.

Sandnes, Hilde (1993). Calculated Budgets for Airborne Acidifying Components in Europe, 1985, 1987, 1988, 1989, 1990 and 1992 (EMEP/MSC-W Report 1/93). Oslo, Norway: Norwegian Meteorological Institute.

Schwartz, Joel (1991). "Particulate Air Pollution and Daily Mortality: A Synthesis." Public Health Review 19, 39-60.

Sisler, J. F., D. Huffman, Douglas A. Latimer, William C. Malm, and M. L. Pitchford (1993). Spatial and Temporal Patterns and the Chemical Composition of the Haze in the United States. Colorado State University, Fort Collins: Cooperative Institute for Research in the Atmosphere.

Stoffer, David S. (1985). "Maximum Likelihood Fitting of STARMAX Models to Incomplete Space-Time Series Data." In Time Series Analysis: Theory and Practice 6, eds. O. D. Anderson, J. K. Ord, and E. A. Robinson, 283-296. New York: Elsevier Science Publishers

Summers, Robert and Alan Heston (1988). "A New Set of International Comparisons of Real Product and Price Levels Estimates for 130 Countries 1950-1985. " The Review of Income and Wealth 35, 1-25.

Tuovinen, Juha-Pekka, Kevin Barrett, and Helge Styve (1994). Transboundary Acidifying Pollution in Europe: Calculated Fields and Budgets 1985-93 (EMEP/MSC-W Report No. 1/94). Oslo, Norway: Norwegian Meteorological Institute.

United Nations (1981). Yearbook of World Energy Statistics: 1979. New York: United Nations Publications.

______ (1984). Air Pollution Studies 1. Airborne Sulphur Pollution: Effects and Control. New York: United Nations Publications.

______ (1985). Air Pollution Studies 2. Air Pollution Across Boundaries. New York: United Nations Publications.

______ (1986). Air Pollution Studies 3. Transboundary Air Pollution: Effects and Control. New York: United Nations Publications.

______ (1987). Air Pollution Studies 4. Effects and Control of Transboundary Air Pollution. New York: United Nations Publications.

______ (1989). Air Pollution Studies 5. The State of Transboundary Air Pollution: Effects and Control. New York: United Nations Publications.

______ (1990a). Air Pollution Studies 6. The State of Transboundary Air Pollution 1989 Update. New York: United Nations Publications.

______ (1990b). Yearbook of World Energy Statistics: 1988. New York: United Nations Publications.

______ (1991a). Air Pollution Studies 7. Assessment of Long-Range Transboundary Air Pollution. New York: United Nations Publications.

______ (1991b). Emission Control Costs and Their Influence on International Emission Reduction Strategies. New York: United Nations Publications.

______ (1992). Air Pollution Studies 8. Impacts of Long-Range Transboundary Air Pollution. New York: United Nations Publications.

______ (1993). Air Pollution Studies 9. The State of Transboundary Air Pollution:1992 Update. New York: United Nations Publications.

_____ (1994). Protocol to the 1979 Convention on Long-Range Transboundary Air Pollution on Further Reduction of Sulfur Emissons. New York: United Nations Publications.

United Nations Environment Programme (1991). Selected Multilateral Treaties in the Field of the Environment, Volume 2. Cambridge: Grotius Publications.

_____ (1993). Environmental Data Report: 1993-94. Oxford: Blackwell Publishers.

Van Huyck, John B., Raymond C. Battalio, and Richard O. Beil (1990). "Tacit Coordination Games, Strategic Uncertainty, and Coordination Failure." American Economic Review 80, 234-48.

Warr, P. G. (1983). "The Private Provision of a Public Good is Independent of the Distribution of Income." Economics Letters 13, 207-211.

Welsch, Heinz (1993). "An Equilibrium Framework for Global Pollution Problems." Journal of Environmental Economics and Management 25, S64-S79.

World Resources Institute (1992). World Resources 1992-93. New York: Oxford University Press.

_____ (1994). World Resources 1994-95. New York: Oxford University Press.