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The Public Economics of the Montreal Protocol on the Ozone Layer

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This paper applies the modern theory of voluntary provision of a pure public good to the behavior of nations to curb chlorofluorocarbons (CFCs) emissions in the late 1980s. By devising empirical tests, we demonstrate that these cutbacks in emissions are entirely consistent with non-cooperative behavior. Regression results indicate that the preponderance of the variation in CFCs emission reductions can be explained by national income and two taste parameters. Rank-ordered statistics provide further support that these variables underlie participation in the initial stipulations of the Montreal Protocol on protecting the ozone layer. These findings suggest that the treaty may be more symbolic than a true instance of cooperation. When our procedures are applied to the Helsinki Protocol, which limits sulfur emissions in Europe, we discover that nations are behaving differently than in the case of CFCs emissions. We attribute this difference to impurely public characteristics of sulfur emissions where depositions vary according to location and other considerations. Our procedures can be applied to a wide range of environmental scenarios including those involving a regional group of developing countries.

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THE PUBLIC ECONOMICS OF THE MONTREAL PROTOCOL ON THE OZONE LAYER

Executive Summary

In recent years, the Montreal Protocol on ozone has been heralded as a monumental achievement in international cooperation. It has been suggested that the Montreal Protocol should serve as a blueprint for cooperative agreements for other global commons problems involving global warming, tropical deforestation, acid rain, and ocean dumping. We present theoretical and statistical findings that suggest that the Montreal Protocol may be more symbolic than a true instance of cooperation.

To support our claim, we apply the theory of the voluntary provision of a pure public good to derive an equation for emission reduction. Reduced ozone emission represents a pure public good, because the preservation of the stratospheric ozone shield provides benefits that are nonrival and nonexcludable on a global scale. That is, ultraviolet radiation protection provided by the ozone shield to one nation does not limit the protection provided and received by other nations. The theory-generated equation relates chlorofluorocarbons (CFCs) emission reductions to a country's income (GNP) and to two taste parameters, involving political rights and geographic location. We test this relationship for the 61 nations that reduced CFCs use between 1986 and 1989, and find support for the noncooperative theory. These emission reductions either took place prior to the Montreal Protocol taking effect or else before mandated cutbacks from 1986 emission levels were required. Moreover, these reductions involved ratifiers and nonratifiers. For the 61 nations in our sample, CFCs reductions from 1986 to 1989 amounted to 41.6 percent of their 1986 CFCs emissions. The treaty instituted a 20 percent reduction, using 1986 as a baseline, in the year commencing on 1 July 1993. Further support for our contention is provided by rank-ordered statistical

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tests, based on correlations. We also use the theory to simulate membership size for the Protocol under two alternative scenarios, and then compare the predicted to the actual participation. Our model underpredicted membership, due, in part, to the sanctions and positive inducements (i.e., financial and technical assistance, delayed compliance) given to developing nations. We, therefore, conclude that these inducements had the desired effect of increasing the number of ratifiers.

We also examine the 1979 Convention on the Long-Range Transboundary Air Pollution and the 1985 Helsinki Protocol, which deals with acid rain in Europe. For sulfur dioxide emissions in the 1980s, our statistical analysis indicates that this noncooperative theory does not apply for this Convention and its Protocol, owing to localized effects and impure public considerations stemming from wind direction and location. The latter implies differential impacts on participants. The contrast between the application of the theory to the ozone and acid rain problems highlights that different global commons issues do not conform to the same underlying behavior of the participants. In consequence, policy reform and prescriptions must be tailored to the particular commons problem; generic policies and treaties are not expected to succeed.

A number of policy recommendations follow from the analysis. First, the Montreal Protocol may be a poor blueprint for other global agreements, especially those involving impure public goods or high abatement costs (e.g., global warming). Second, the wealthiest CFCs emitters can be expected to adhere to the Protocol without the need of an enforcement mechanism, because the net benefits from doing so is apparently positive. Self-interests motivate compliance. Third, an increase in the number of democratic countries is apt to increase the number of nations that will take steps to curb

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transboundary emissions. Thus, increases in political freedoms, achieved after 1989 by the transitional countries of Central and Eastern Europe, may serve to increase compliance with the Montreal Protocol's provisions. Fourth, foreign aid that increases the GNP level of developing and transitional economies should accelerate the adherence to the required reductions in CFCs emissions. An environmental dividend can stem from foreign aid, because the preservation of environmental assets responds positively to augmented levels of GNP. Fifth, the use of side payments, a deferred adherence schedule, and the threat of trade sanctions augment the number of participants. The accomplishment, in terms of ozone protection in the future, from this increase in group size is yet to be known, since many of these countries did not emit CFCs. Sixth, the behavior of European nations with respect to the Helsinki Protocol and SO_2 emissions did not abide by the theoretical predictions of the voluntary provision of a pure public good. The acid rain problem will need controls that differ from those of the ozone-depletion problem.

THE PUBLIC ECONOMICS OF THE MONTREAL PROTOCOL ON THE OZONE LAYER*

1. Introduction

In recent years, there has grown an increased awareness of transboundary pollution that places environmental assets at risk both globally and regionally. Traditional nation-state jurisdictions need not coincide with the economic domain over which the economic impacts of consumption and production activities extend. Globally, manmade pollutants have degraded the stratospheric ozone shield, the oceans, the atmosphere, and the biodiversity of the planet; regionally, these pollutants have harmed aquifers, rivers, lakes, soils, and forests.[1]

Many transboundary pollution problems share two common features: strategic interactions among nations and public good properties. Strategic interactions occur when the strategic choice or action of one nation is dependent on its beliefs concerning the choices of the other nations. To account for these strategic interactions, a game theory formulation is often presented.[2] Public good properties arise when the benefits (costs), derived from limiting (not limiting) the pollutant, provide consequences that are nonrival and nonexcludable to a set of nations. A good has nonrival benefits when a unit of the good can be consumed by one agent without detracting, in the slightest, from the consumption opportunities still available for others. When the benefits of a good must be made available to all because exclusion is too costly, then these benefits are nonexcludable.

Limiting global and regional pollutants are characterized to some extent by nonrivalry and nonexcludability. In the case of stratospheric ozone, the release of chlorofluorocarbons (CFCs) and other substances thins the ozone shield that protects plants and animals from harmful ultraviolet radiation. This thinning has consequences for countries worldwide and is, thus,

nonexcludable. Furthermore, one nation's increased exposure to enhanced ultraviolet radiation does not lessen the risks to any other nation; hence, nonrivalry is clearly present. A small amount of impurity may arise, since the thinning tends to be most pronounced in the springtime at higher latitudes near the poles.

The purpose of this paper is to apply recent theoretical advances in the voluntary provision of pure public goods[3] to analyze cutbacks in CFCs emissions that, in large part, preceded the ratification and institution of the Montreal Protocol on Substances that Deplete the Ozone Layer. It is our contention that the Montreal Protocol was enacted because it codified reductions in CFCs emissions that polluters were voluntarily prepared to accomplish. To support this viewpoint, we use the above-mentioned theoretical advances to derive an empirical equation that predicts a linear relationship between voluntary reductions in CFCs emissions and national income, conditional on taste parameters involving political and geographical considerations. We then estimate a Box-Cox transformation and demonstrate that the hypothesized relationship is essentially linear. Our analysis is noteworthy, because it provides the most sophisticated test to date of the modern theory of the voluntary provision of pure public goods. Nonparametric tests lend further evidence to the voluntary nature of CFCs cutbacks in the late 1980s. We also use simulations to identify the ratifiers and their emission reductions. The model's underprediction of group size may indicate that the threat of trade sanctions and other inducements may have increased the number of ratifiers.

Our findings suggest that the Montreal Protocol may be more symbolic than a true instance of a cooperative equilibrium, because nations' CFCs reductions prior to the treaty taking effect were greater than the mandated

cuts. We, however, caution that to conclude that the Montreal Protocol is not an instance of cooperation would require further tests that the absence of data for the post-protocol period makes impossible at this time.

We also contrast the Montreal Protocol and the reductions in CFCs emissions to the 1979 Convention on Long-Range Transboundary Air Pollution (LRTAP) and cutbacks in sulfur dioxide emissions. The latter situation does not fit the theory associated with the voluntary provision of a pure public good because of impure public considerations (also see Murdoch and Sandler, 1993).

Others have identified special features of the Montreal Protocol that differentiate it from other proposed forms of global collective action, such as global warming. These features concern the relatively large marginal benefits and relatively small marginal costs that derive from unilateral actions. Barrett (1992), for example, argued that the noncooperative solution will not differ much from the cooperative outcome. Poterba (1992) and Sandler (1992a, 1992b) characterized the Montreal Protocol's ratification as being facilitated by scientific certainty, the availability of substitutes, and the concentration of CFCs production interests. Our approach differs from these earlier studies, because we use public goods theory to derive formal tests that support the notion that the Protocol is consistent with a noncooperative response. Our analysis also differs from that of Congleton (1992) who related the ratification of the Vienna Convention of 1985 and the Montreal Protocol to political and market institutions. As such, Congleton (1992) did not explicitly account for public good attributes and did not include gross national product (GNP) levels of the participating nations.[4]

In the late 1980s, CFCs users (see World Resources Institute, 1990, 1992) primarily consisted of developed countries and some transitional

economies. Thus, our specific analysis is primarily applicable to these countries. Developing nations were not heavy users of CFCs during the time period for which data is available. Our methodology is sufficiently general that it could be applied to environmental problems confronting regional groups of developing nations (e.g , erosion problems stemming from deforestation, acid rain concerns). Hence, we do feel that our analysis could, someday, enlighten people about policy reform in the developing economies.

The remainder of the paper contains seven sections. In section 2, we provide background to the ozone problem and the Montreal Protocol. Section 3 presents the underlying theoretical model for the private provision of public goods, while section 4 applies this model to the specific case of homothetic tastes for homogeneous and heterogeneous individuals. The demand for reduced CFCs emissions are examined in section 5 with ordinary least squares and Box-Cox nonlinear least squares estimates. Empirical results are presented that support our voluntary provision of public good interpretation. Section 6 contains further support of the noncooperative interpretation and includes nonparametric rank-ordered statistics and simulations. In section 7, we examine the convention on LRTAP to show that it does not abide by the pure public good interpretation. Conclusions and policy recommendations follow in section 8.

2. Background

2.1 The Stratospheric Ozone Shield

Despite its small concentration in the earth's atmosphere, representing less than one part per million, ozone absorbs much of the ultraviolet radiation of the sun and, thus, protects all living organisms from its harmful effects. Any dissolution of the stratospheric ozone shield would not only

increase the risk of skin cancer to humans, but would also threaten food supplies by adversely affecting phytoplankton at the base of the marine food chain. Disastrous consequences could result. The Environmental Protection Agency (EPA) estimated that the implementation of the Montreal Protocol of 1987 could save the United States $6.4 trillion by 2075 in reduced costs associated with skin cancers (EPA, 1987a, 1987b). In the absence of the Protocol, skin cancer incidence was based on an annual growth of CFCs use at 2.5 percent through 2050. The long-run cost from cutting CFCs use, as mandated by the Protocol, was estimated to be between $20 and $40 billion during the 1989-2075 period, given these projected growth rates (Morrisette et al., 1990, p. 16).

As early as 1974, Molina and Rowland theorized that released CFCs could migrate upwards to the stratosphere where they could be broken down by sunlight, thus giving up chlorine which would combine with ozone (Morrisette, 1990, p. 10). In the process, the ozone shield would be depleted. CFCs are used in air conditioning, refrigerators, aerosols, insulating foam, and the cleansing of circuit boards. With each application, CFCs escape into the atmosphere. Concern was heightened because CFCs could remain in the atmosphere for over 100 years; hence, the impact of earlier releases are not fully experienced until a considerable delay. Even a complete ban on CFCs would not end the depletion of the ozone layer for some time into the future.

Subsequent findings, provided by scientists with the Department of Transportation, a Federal Task Force on Inadvertent Modification of the Stratosphere, and the National Academy of Science, convinced the EPA to prohibit the non-essential use of CFCs as aerosol propellants in 1978 (Morrisette et al., 1990, pp. 10-12). Other countries, except for Canada (in 1978), Sweden (in 1979), and Norway (in 1981), did not follow the U.S. ban,

because there existed disagreement in the scientific community over whether CFCs really depleted the ozone layer and, if so, how the process took place. This disagreement ended after further monitoring of the ozone layer and more complete theoretical formulations.

In 1985, the British Antarctic Survey presented evidence that an alarming 40 percent drop (from 1964 levels) in the springtime atmospheric concentration of ozone took place over Halley Bay, Antarctica, between 1977 and 1984. This so-called "hole" in the ozone layer of the stratosphere then drifts northward during the summer and mixes with other air masses, thus allowing the depletion to be shared worldwide on an equal basis.

Recent scientific evidence has formed the following picture of the depletion process:[5] Once released into the atmosphere, CFCs are broken down by sunlight into chlorine, which, in turn, combines with nitrogen dioxide, methane, and ozone to form stable reservoirs of chlorine nitrate and hydrochloric acid. Throughout this initial process, ozone depletion is modest. The real destruction takes place over the polar regions during the long cold winters when stratospheric clouds of nacreous acid and nitric acid trihydrate trigger a chemical reaction that causes the stable reservoirs of chlorine to release molecular chlorine. When sunlight returns in the spring, the free chlorine along with ozone combine to form chlorine monoxide and oxygen. In the process, ozone is destroyed. Stable chlorine reservoirs do not form under these frigid conditions, because the nitrogen compound, required for reservoir formation, precipitates. Since the South Pole is colder than the North, larger ozone holes have been observed over the Antarctic.

The uniform mixing of the ozone layer in the summertime reinforces the pure publicness of the ozone depletion process. Only during the springtime

when the holes are formed are the higher latitudes differentially impacted. Eventually, the thinning is spread worldwide. Though some impure publicness properties are present, the CFCs emission problem comes very near to satisfying both requirements of pure publicness.

2.2 Montreal Protocol of 1987

Just prior to the discovery of the Antarctic ozone hole, nations negotiated the Convention for the Protection of the Ozone Layer in Vienna on 22 March 1985. This precursor to the Montreal Protocol mandated the ratifiers to study the harmful effects of CFCs emissions on the ozone layer. Nations were committed to monitor the ozone layer, to exchange scientific findings, and to develop domestic programs for limiting ozone-depleting substances.[6] By 1989, 27 countries had signed the Vienna Convention or had approved domestic legislation to accomplish its ends.

On 16 September 1987, the Montreal Protocol extended the Vienna Convention by setting explicit limits to the emission of ozone-depleting substances, particularly CFC-11 and CFC-12. The Montreal Protocol entered into force on 1 January 1989 following the required signatures of more than the required 11 ratifiers,[7] and included the following primary features:

(1) From their commitment date to 1 July 1993, ratifiers must reduce their annual consumption and production of CFCs to 1986 levels.

(2) From 1 July 1993 to 30 June 1994 and during each year thereafter until 1 July 1998, ratifiers' annual production and consumption of CFCs cannot exceed 80 percent of their 1986 levels.

(3) From 1 July 1998 and thereafter, ratifiers' annual production and consumption of CFCs cannot exceed 50 percent of their 1986 levels.

(4) To meet obligations, emission transfers between Protocol parties are

permitted.

(5) To induce ratification, Protocol parties must ban the import of controlled substances from nonratifiers starting in 1990. Beginning on 1 January 1993, ratifiers cannot export ozone-depleting substances to nonratifiers.

(6) For developing countries whose annual consumption is less than 0.3 kilograms (kgs) per capita on their entry date, a ten-year delay in terms of compliance was granted. A promise of technical and financial assistance to developing countries was made.

Ratifiers of the Montreal Protocol were automatically considered to be parties to the Vienna Convention. During 1989, the ratifiers were only obligated to meet 1986 emission levels; this fact becomes important for interpreting the empirical findings. Developing nations had a great inducement to ratify the Protocol, because they could delay compliance by ten years, gain technical and financial assistance, and be exempt from trade sanctions.

During 1990, scientific evidence indicated that the thinning of the ozone layer had worsened and that a large hole had opened over the North Pole. On 29 June 1990, the Montreal Protocol was strengthened with a set of amendments. Most notable, ratifiers accelerated their responsibilities by promising to reduce production and consumption levels of CFCs during 1995 to 50 percent of the 1986 levels. For 1997 and the following two years, these levels of CFCs could not exceed 15 percent of 1986 levels. By 1 January 2000, CFCs production and consumption must be zero, except for the recycling of previously produced CFCs. Amendments also strengthened and better defined trade restrictions, and established the Multilateral Fund to assist developing countries, known as "Article 5 nations." The amended protocol entered into

force on 10 August 1992, following the required 20 signatures..

3. Theoretical Considerations

The theoretical model draws from the work of McGuire (1974), Andreoni (1988), Andreoni and McGuire (1993), and others who used a subscription model of public good contributions to identify contributors. We assume that a nation's preferences for a global public good, G, is represented by a quasi-concave, strictly increasing utility function,

$$U_i = U_i(y_i, G), \tag{1}$$

where y_i is the ith nation's consumption of a composite private good and G is the total amount of the public good available for consumption, so that

$$G = \sum_{i \in C} g_i. \tag{2}$$

In eq. (2), g_i is the ith nation's contribution to the public good and C denotes the set of contributors ($g_i > 0$). Total contributions can also be written as $g_i + G_{-i}$, where G_{-i} is the sum of contributions from contributors other than nation i, so that

$$G_{-i} = \sum_{j \neq i} g_j. \tag{3}$$

Initially, we normalize all prices to be unity and write the ith nation's linear income constraint as

$$w_i = y_i + g_i, \tag{4}$$

where w_i denotes national income. A full-income budget constraint follows from adding G_{-i} to both sides of (4) to give

$$w_F^i = w_i + G_{-i} = y_i + G, \tag{5}$$

where w_F^i denotes the ith nation's full income--income plus spillins of public good benefits. To derive the nation's demand for the total amount of the public good, we depict the nation as solving the following maximization

problem:

$$\max_{y_i, G}\{U_i(y_i, G) \mid w_i + G_{-i} = y_i + G;\ G \geqq G_{-i}\}. \tag{6}$$

In eq. (6), the inequality constraint indicates that the ith nation is a contributor and, hence, a member of C only when $G > G_{-i}$, so that $g_i > 0$. Noncontributors choose a G that equals G_{-i} and contribute nothing. The Kuhn-Tucker first-order conditions imply the following continuous demand function,

$$G = \max\{f(w_i + G_{-i}),\ G_{-i}\}, \tag{7}$$

for the pubic good. When contributions are positive, the nation's demand for G is $f(\cdot)$; otherwise it is G_{-i}. A Nash equilibrium results when we have a vector of individual contributions, g_i, that maximize utility in (1) subject to (4) and the constancy of the best-response level for spillins, G^*_{-i}. At the Nash equilibrium, neither contributors nor noncontributors would unilaterally want to change their public good contributions. This equilibrium is unique provided that all goods have positive income elasticities, which we, henceforth, assume (Bergstrom, Blume, and Varian, 1989, Theorem 2-3).

For the ozone shield, g_i denotes the reduction in ozone-depleting CFCs emissions and y_i represents all other goods. To maintain tractability and facilitate analogy with the public goods literature, we analyze only the nation's behavior with respect to current emission policy. Although this approach ignores dynamic stock adjustments,[8] it is consistent with the language and articles of the Montreal Protocol. Furthermore, this approach agrees with other game approaches by Barrett (1992), Mäler (1989), and Sandler (1992c). The Nash assumption is especially important and implies each nation pursues its own self-interests independently.

To distinguish contributors, we must put more structure on the taste patterns by assuming that nations have identical tastes but different income

endowments, w_i. This does not mean that all nations have the same demand for the public good; rather, it means that, for normal goods, the nations' demand for the public good can be rank ordered by income so that $g_i > g_j$ when $w_i > w_j$ (Bergstrom, Blume, and Varian, 1986; Andreoni, 1988). If nations' indices are assigned according to their income ranks with $i > j$ for $w_i > w_j$, then we can utilize the result in Bergstrom, Blume, and Varian (1986, Fact 4) to identify the critical income level, w^*, below which no nation contributes. Specifically, a nation's equilibrium contribution, g_i^* is as follows:[9]

$$g_i^* = \begin{cases} w_i - w^* & \text{if } w_i > w^*, \\ 0 & \text{if } w_i \leqq w^*, \end{cases} \tag{8}$$

where the critical income w^* equals $f^{-1}(G^*) - G^*$. Eq. (8) indicates that pollution reduction is a linear function with a unit slope coefficient on income. It also follows that all contributors consume the same amount of the private good, which equals w^*. Based on eq. (8), total equilibrium contributions equal

$$G^* = \sum_{i=1}^{n} g_i^* = \sum_{w_i > w^*} (w_i - w^*). \tag{9}$$

This equation is used in our simulations and indicates that total contributions can be expressed as the tail of a cumulative distribution of income.

We next consider the case where the price of the public good is not normalized and equals p. In equilibrium, the level of total contributions satisfies

$$G^* \geqq f(w_i + pG_{-i}^*, p). \tag{10}$$

By the same procedure used to derive eq. (8), eq. (10) can be shown to imply

$$g_i^* = \begin{cases} w_i/p - w^*(p)/p & \text{if } w_i > w^*(p), \\ 0 & \text{if } w_i \leqq w^*(p), \end{cases} \tag{11}$$

where $w^*(p) = f^{-1}(G^*, p) - pG^*$. In eq. (11), the critical income level is conditional on price.

Based on Andreoni (1988, pp. 64-66), our last general case allows nations' tastes to differ according to a continuous taste parameter, θ, so that

$$U_i = U_i(y_i, G; \theta). \tag{12}$$

In eq. (12), θ is used to index the various (finite) types of nations and may be a vector of exogenous taste parameters. For an equilibrium with normalized prices, we have

$$G^* \geqq f(w_i + G^*_{-i}; \theta) \tag{13}$$

for each i, in which $f(\cdot)$ is the demand for the public good among the contributors. Using eq. (13), we can employ the earlier procedure to identify contributors as follows:

$$g_i^* = \begin{cases} w_i - w^*(\theta) & \text{if } w_i > w^*(\theta), \\ 0 & \text{if } w_i \leqq w^*(\theta), \end{cases} \tag{14}$$

where $w^*(\theta) = f^{-1}(G^*; \theta) - G^*$. This result means that there is a critical income level for <u>each</u> class of nations. Type θ nations will contribute whenever their income exceeds $w^*(\theta)$. Total contributions to the public good now equals

$$G^* = \sum_{\theta} \sum_{w_i > w^*(\theta)} [w_i - w^*(\theta)], \tag{15}$$

where contributions are summed over and within each taste class.

Eq. (14) indicates that a nation's demand for a global public good depends on national income and taste attributes.[10] For instance, the θ parameter could relate to the country's geographical position in terms of latitude. Temperate and arctic countries may have a greater preference for curbing CFCs emissions than tropical nations owing to greater springtime

exposure at those latitudes to ultraviolet radiation. Tastes may also differ between autocratic and democratic regimes. In an important paper, Congleton (1992) theorized that autocratic regimes will do less to protect the ozone shield, insofar as these autocracies confront a higher relative price for pollution abatement than their democratic median-voter counterpart. Congleton also argued that autocracies are less risk averse and, hence, less interested than democracies in insurance-type actions that protect against contingencies such as ozone depletion. Given the relatively short-term nature of most autocracies,[11] he also hypothesized that such governments would not be as concerned about the long-run consequences of ozone depletion. Olson (1993) characterized autocracies as maximizing tax revenues and maintaining their monopoly rights over these taxes. As such, autocracies should be suspicious of protocols that could impose taxes or else could mandate contributions to a multilateral fund used to provide technology transfer and financial assistance to others. Olson indicated that autocracies would provide public goods when their provision augments taxable income sufficiently to finance the goods and leave some net gain.[12] No augmentation in taxable income can be expected to arise from cutting CFCs emissions worldwide. Autocracies may, therefore, be less willing than democracies to support ozone protection. Within the group of autocracies or democracies, the theory above predicts that the cutback in CFCs emissions will be related to income.

Andreoni (1988) also showed that as n goes to infinity the class of contributors converges to a single type, consisting of those agents with the strongest or most-supportive taste characteristics. In the case of ozone, democracies with the highest income levels may be the only nations willing to curb ozone emissions. This conclusion will be lessened to the extent that specific inducements are given to nations in terms of technical assistance,

aid, or a delay in compliance.

4. Specific Example: Homothetic Tastes

To provide a set of simulations in section 6, we need a specific utility function to attribute to the nations. A broad class of utility functions consists of homothetic functions and includes Cobb-Douglas and constant elasticity of substitution (CES) functions as special cases. With a homothetic function, the income consumption path is a linear ray out of the origin in the indifference curve diagram with G and y on the two axes, because the marginal rate of substitution between G and y (MRS_{Gy}) is solely dependent on the ratio $G/y = k$. For a given set of relative prices, the consumption <u>proportion</u> k is determined and does not change with either income or spillins, since both changes imply the same relative prices.

In the case of identical homothetic preferences, different endowments, and normalized prices, demand for total contributions is

$$G^* = ky_i^* = k(w_F - G^*), \qquad i \in C, \tag{16}$$

at equilibrium, where w_F is full income. This equation can be rearranged to yield[13]

$$g_i^* = \begin{cases} w_i - (1/k)G^* & \text{if } w_i > w^*, \\ 0 & \text{if } w_i \leqq w^*, \end{cases} \tag{17}$$

where cut-off income w^* simply equals $(1/k)G^*$. Total contributions equal[14]

$$G^* = \sum_{w_i > w^*} [w_i - w^*]. \tag{18}$$

An increase in k implies that G must be consumed in greater proportion as compared with other goods, so that w^* falls and, hence, the number of givers increases. Once again, we could introduce a taste parameter θ and derive an equation for total contributions analogous to eq. (15). Within each class of

positive contributors, g_i^* equals $w_i - [1/k(\theta)]G^*$. A stronger taste parameter would make for a higher k and, thus, a lower critical income level for the taste class.

Since we know the income distribution over nations, we can pick various k levels and use eq. (18) to find w^* and, hence, the size of the contributing group. These simulations can be compared to the actual set of contributors to assess the noncooperative theory of public goods as a determinant of transnational participation in the Montreal Protocol.

5. Empirical Results

5.1 Background

Eqs. (8), (11), and (14) provide the theoretical predictions that can be tested with observed data. Eq. (8) suggests that if we measure the voluntary contributions (g_i) and the income (w_i) of countries and then plot these data with income on the horizontal axis and contributions on the vertical axis, the data should lie on either the horizontal axis ($g_i = 0$) or on the 45° line beginning at w^*. If we limit our investigation to countries with positive voluntary contributions, then the data should lie on the 45° line. This prediction is, in principle, testable, but a major obstacle is to measure g_i and w_i precisely. If we assume random errors in measuring g_i and w_i, then

$$g_i = \beta_0 + \beta_1 w_i + \epsilon_i \tag{19}$$

is a reasonable empirical model for the data-generating process described in eq. (8). β_0 and β_1 can be estimated with ordinary least squares (OLS). We can test how well the model adheres to the 45° line by assuming that the ϵ_is are independent and normally distributed with mean zero and standard deviation σ.

Although the regression model described in eq. (19) provides a simple method for testing whether the slope of the hypothesized line is unity (β_1 = 1), it does not facilitate a test of linearity. One means to test linearity is to estimate the transformation parameter of the Box-Cox transformation (Box and Cox, 1964; Spitzer, 1982). With λ denoting the transformation parameter, the model becomes:

$$g_i = \beta_0 + \beta_1[(w_i^{\lambda} - 1)/\lambda] + \epsilon_i. \tag{20}$$

This model is nonlinear in λ, requiring a nonlinear least squares estimator. A test for linearity is based on λ. If λ is equal to one, then the model is linear with respect to w_i. Values for λ other than one generate the most common transformations; e.g., the natural logarithmic transformation (λ = 0), the quadratic (λ = 2), and the square root (λ = 0.5).

Eq. (11) suggests a pattern for the data that is similar to that described in eq. (8). For contributing nations, the difference is that the predicted slope is equal to 1/p instead of one. By interpreting β_1 as an estimate of 1/p, we can still use the model in eq. (20) to test the linearity prediction.

According to eq. (14), the linearity of the relationship between w_i and g_i only holds within each group of nations as defined by the θ parameter. To implement an empirical test of this prediction, we need to measure the taste differences of nations. Let $\boldsymbol{\theta}_i$ denote a 1 by k vector of observable taste measures and $\boldsymbol{\gamma}$ denote a k by 1 vector of unknown parameters. Then a statistical model based on eq. (14) is

$$g_i = \beta_0 + \beta_1[(w_i^{\lambda} - 1)/\lambda] + \boldsymbol{\theta}_i\boldsymbol{\gamma} + \epsilon_i. \tag{21}$$

If the Andreoni (1988) model is more appropriate, then we should see significance in the estimates for the $\boldsymbol{\gamma}$ parameters and more linearity in the

relationship between g_i and w_i when we compare eq. (21) to (20).

A potential problem with the regression analysis concerns whether the observed measures are consistently measured across countries. If there are nonrandom measurement errors in the country data, then we could incorrectly conclude a linear (or nonlinear) relationship. There are obvious consistency problems measuring variables like income cross-nationally; thus, this is a serious consideration. We try to ensure the robustness of our conclusions in two ways. First, we analyze the influence of individual observations using the methods described in Belsley, Kuh, and Welsch (1980), which facilitates a qualitative assessment of the robustness of the regression estimates. Second, we study the correlations of ordered ranks of the data. Analyzing ordered ranks, in this case, is appealing because the conclusions are robust with respect to data errors, provided that the rankings remain the same. We feel that the combination of a careful consideration of influential observations and the analysis of ordered ranks allows us to state our empirical conclusions with greater confidence.

5.2 Data and Variable Definitions

The empirical tests focus on the voluntary contributions to the protection of the ozone layer. Our primary measure of g_i is $DEMIT_i$, which is the change in the CFCs emissions for country i from 1986 to 1989 (EMIT86 – EMIT89). A positive value for $DEMIT_i$ indicates that country i reduced CFCs emissions, thus making a positive contribution to the protection of the ozone layer. In total, 61 nations had positive values for $DEMIT_i$. To test for voluntary behavior, only these countries, whether they ratified the Montreal Protocol or not,[15] are included in the regression estimates. The data for EMIT86 and EMIT89 are reported in World Resources Institute (WRI)(1990, 1992).

Since 1986 is the benchmark year for the Montreal Protocol and 1989 is before any emission reductions (contributions) from 1986 levels are mandated under the treaty, $DEMIT_i$ is a satisfactory measure of voluntary contributions.

To measure income (w_i), we use gross national product in 1985 (GNP85). The choice of year is primarily pragmatic; data is more readily available for 1985 than, say, 1990. For the majority of the countries, GNP85 is obtained from the World Tables produced by the World Bank (1990). For some nations, in particular those with nonmarket economies, the GNP data is taken from the World Fact Book: 1989, produced by the U.S. Central Intelligence Agency (CIA, 1989).[16]

We use two measures for components of the vector (θ) of taste variables. The first is GASTIL, which is the sum of Gastil's (1986) index of civil liberties and index of political rights. Gastil's indices are integers, with 1 representing the most liberties and rights and 7 representing the least. Thus, GASTIL takes on integer values from 2 to 14. A country with a value of 2 (indices of civil liberties and political rights both equal to 1; e.g., the U.S.) would be considered the most "free." In some of the analysis, we use FREE: FREE equals 1, if GASTIL is less than or equal to 4; FREE equals 2, if GASTIL is greater than 4 but less than 10; and FREE equals 3, if GASTIL is greater than or equal to 10.

The second empirical measure of tastes is based on geographical location, in which LAT is defined to equal 1 for all countries located above the Tropic of Cancer, to equal 2 for all countries between the Tropic of Cancer and the Tropic of Capricorn, and to equal 3 for the countries below the Tropic of Capricorn.[17] Dummy variables corresponding to LAT were also defined. Thus, L1 is 1 when LAT is 1, and 0 otherwise; L2 is 1 when LAT is 2, and 0 otherwise; and L3 is 1 when LAT is 3, and 0 otherwise.

A summary of the empirical variables and their definitions is displayed in Table 1. Basic summary statistics are presented in Table 2. The summary statistics in Table 2 facilitate a comparison of the entire data set to the subsample of 61 nations with positive values for $DEMIT_i$. On average, the voluntary contributors have greater GNPs in 1985, lower GASTIL measures, and are more likely to be above the Tropic of Cancer. Table A1 in the appendix shows all of the countries, GNP85, DEMIT, GASTIL, and their status with respect to the Montreal Protocol.

5.3 Regression Results

Nonlinear least squares estimates of the parameters in eqs. (20) and (21) are presented in Table 3. The estimates on GNP85 and LAMBDA are significant at conventional levels in all three specifications. The coefficient on the GASTIL index is negative and significant in both Models 2 and 3, indicating that nations with fewer freedoms (political rights and civil liberties) voluntarily contribute less when income is held constant. This finding is consistent with the predictions in Congleton (1992) and Olson (1993). In Table 3, the latitude dummy variables are marginally insignificant, because the critical value for the t-statistics is 1.299 at the .20 level of significance (two-tailed test). The northern latitudes are the left-out category; hence, the estimates on L2 and L3 are relative to L1. The negative signs mean that the expected value of $DEMIT_i$, conditional on income and freedoms, is less for the middle and lower (southern) latitude countries when compared to the expected value of the northern latitude group. The R-squares are very high for cross-sectional data, which may indicate an outlier problem that we investigate below.

We are particularly interested in the estimates for the Box-Cox LAMBDA

transformation parameter, whose estimate from Model 1 is significantly different than one. The asymptotic standard error is .04, thus yielding a 95% confidence interval of .822 ± .08. Andreoni's (1988) analysis indicates that linearity between income and contributions may not hold over all members of the group, but should hold within subclasses defined by taste parameters. By examining the three estimates for LAMBDA, we see some empirical support for Andreoni's models. As we statistically control for the tastes of the members, measured by freedoms and geographic location, the point estimate for LAMBDA moves closer to one; however, the 95% confidence interval estimates never include one.

From a purely statistical point-of-view, the results concerning the Box-Cox transformation parameter provide sufficient evidence o reject the noncooperative theory presented in section 3. At the practical level, however, we cannot ignore the fact that the point estimate of LAMBDA is very close to one. To better understand this finding, we estimated the linear models ($\lambda = 1$) using ordinary least squares (OLS) and give the results in Table 4. The qualitative conclusions are essentially the same, when comparing the nonlinear estimates in Table 3 to the OLS estimates in Table 4. A notable difference is that the estimate on L2 is more precise in Table 4.

How do the estimates of $\partial g_i/\partial w_i$ vary between the two specifications? This is difficult to answer by just eyeing the estimated parameters. Recall that the noncooperative theory predicts that this derivative is constant; i.e., it is equal to one (for normalized prices) or 1/p. Thus, it is important to be able to determine the extent of the nonlinearity implied by the Box-Cox Model. To facilitate a comparison of the estimated nonlinear and linear models, we graphed both estimated relationships in Figure 1, with $GNP85_i$ measured along the horizontal axis and $DEMIT_i$ along the vertical axis.

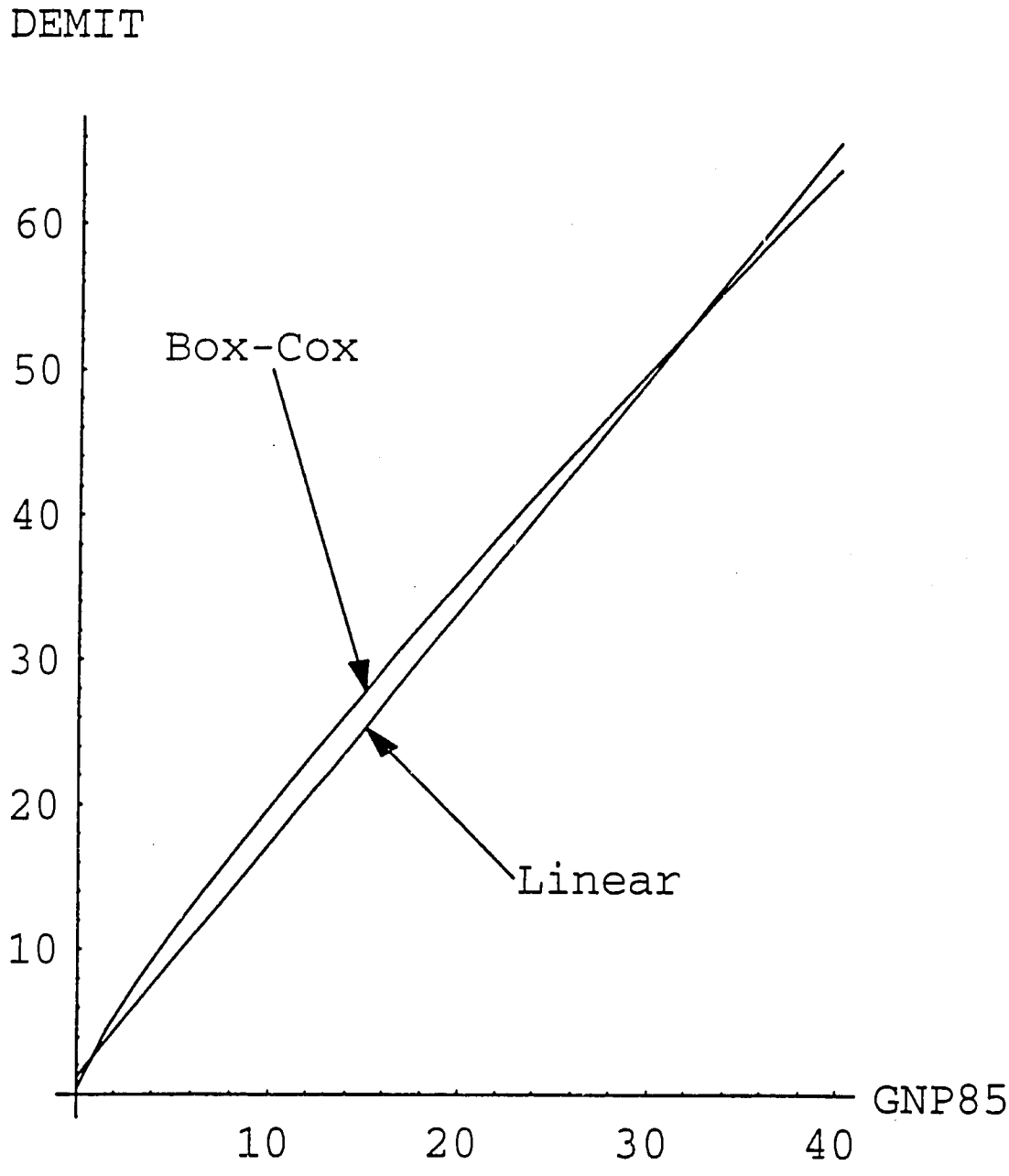

Figure 1. Estimated Linear and Box-Cox functions.

The lines are based on Model 3 estimates, with the average values for GASTIL, L2, and L3 used to locate the vertical intercept.[18] In Figure 1, we see that the linear and the Box-Cox model are very close to one another. The linear model slightly underpredicts (assuming the Box-Cox model is the true model) $DEMIT_i$ for the lower levels of $GNP85_i$ and slightly overpredicts at the higher levels. The prediction error is, however, noticeably small. An analysis of Figure 1 suggests that the linear model is actually a very good approximation to the Box-Cox model. Rather than rejecting the noncooperative theory, we suggest that the Box-Cox model provides strong support for the theory. The estimated slope is not one, meaning that the appropriate interpretation for the slope estimate is 1/p. Converting $DEMIT_i$ to grams and $GNP85_i$ to dollars, we find that the estimated implied price of g_i is \$62.03 per gram.[19]

Heteroskedasticity is always a possibility with cross-sectional data. With White's (1980) general test for heteroskedasticity on Model 3, we fail to reject the null hypothesis of homoskedastic errors. The hypothesis is rejected for model 1, indicating a specification error in that model. This result provides additional support for Andreoni's characterization of the theory, since the data appear to fit the statistical model when the taste parameters are included.

Because the ordinary least squares and the nonlinear least squares (NLS) estimators minimize the sum of squared deviations, they are sensitive to "outliers." To check the robustness of our primary conclusion (linearity between $GNP85_i$ and $DEMIT_i$), we analyze the coefficient sensitivity for Model 3 of the OLS estimates using the diagnostic measures proposed by Belsley, Kuh, and Welsch (1980, ch. 2). A particularly relevant diagnostic measure is $DFBETA_i$, which shows the impact on the estimated regression parameter from dropping the ith observation. Focusing on the relationship between DEMIT and

GNP85, we find two observations, the U.S. and U.S.S.R., with $DFBETA_i$s that fall outside the acceptable bounds established by Belsley, Kuh and Welsch. Moreover, both of these observations are identified as influential by the diagonal elements of the "hat matrix" (referred to as leverage points) and by the "COVRATIO measure." For the observations under consideration, the leverage measure indicates that the values of the independent variables are relatively far away from the sample mean values. The COVRATIO measure indicates that the variance-covariance matrix is relatively sensitive to the observation under consideration. The high degree of leverage for the US appears to be tied to its high GNP, while for the USSR it appears to be tied to the high GASTIL index.

We investigate the impact of these two observations on our estimate of LAMBDA by re-estimating the Box-Cox model without these observations. When just the U.S. <u>or</u> the U.S.S.R. observation is dropped, the estimate for LAMBDA do not change dramatically. When, however, both points are dropped, the NLS estimate for LAMBDA increases to 1.087 with a standard error of 0.15 (t-ratio equal to 7.2). In this case, the 95% confidence interval contains one, and we cannot statistically rule out the linear model. This finding indicates additional support for our hypothesis of linearity; <u>the influential observations appear to be the cause of the slight nonlinearity identified by the Box-Cox model</u>.

The Belsley, Kuh, and Welsch (1980) procedures provide tools for checking the role of individual observations in regression. They do not give guidelines for dropping data points. We argue that the 61 country data set is still the most appropriate for our tests. However, we feel some confidence in stating that the "true relationship" between income and voluntary contributions is nicely approximated by the linear specification.

6. Additional Analysis

6.1 Rank Order Correlation

A potential problem with the regression analysis concerns measurement error in the primary variable of interest--$GNP85_i$. The gross national product must be converted to U.S. dollars and, regardless of the methodology used to convert the data, some potential for non-random error exists. Moreover, for some countries (e.g., U.S.S.R.), we used the CIA's (1989) estimate of GNP. Recent developments in East Europe have illustrated that the CIA generally overestimated the strength of the communist economies in the 1980s. Such departures from random error could bias our tests of linearity. (Recall that one of the influential observations was the U.S.S.R.)

In order to further investigate the robustness of our linearity conclusions, we compute the Spearman rank correlation between $GNP85_i$ and $DEMIT_i$ by taste group as identified by the GASTIL index and latitude. The advantage of the rank correlations is that they are robust with respect to measurement error as long as the error is not sufficient enough to change a country's rank. Failing to reject the null hypothesis of no linear association would certainly indicate strong evidence against the noncooperative theory. On the other hand, rejecting the null hypothesis would support our earlier conclusion with respect to linearity.

The Spearman rank correlation statistics are presented in Table 5. The overall correlation is 0.840, displayed in the cell identified by the last row and last column of the table. The estimate is statistically significant (asymptotic t-ratio is equal to 16.8), suggesting rejection of the null hypothesis of no association. As the group becomes more homogeneous, we should find that the correlation coefficient approaches one. This happens for

the countries above the Tropic of Cancer defined by LAT = 1 (the first column of correlation statistics in Table 5) and for the countries defined by FREE = 1 (the first row of correlation statistics in Table 5). On the other hand, when LAT is equal to 2 or 3 and FREE is equal to 2 or 3, the estimated correlation statistics fall. An obvious problem here is that within some of the cells, the number of observations is rather small; hence, we are reluctant to place too much emphasis on the cell-by-cell analysis. Generally, the statistics presented in Table 5 indicate rejecting the null hypothesis of no correlation. Thus, they appear to support our parametric analysis.

6.2 Simulations

The previous section concerned a statistical analysis of the world data, in which statistics were used to make inferences about the true data-generating model. The simulation methodology differs from the statistical methodology, since the former assumes that we know the true data-generating model, except for some parameters. In order to simulate what happens when the unknown parameter changes, the model is "run" for various values of the unknown parameters.

The model is presented in eqs. (17) and (18). Using these equations and the values for income in our data set, we want to find the number of voluntary contributors for each value of k. The solution requires sorting the data by income in descending order (w_1 is the richest country) and then finding all countries with positive values for g_i^*. The model is solved for each i (i = 2, 3, 4, ...) until g_i^* is ≤ 0. Once the cutoff country is found, we know that nations with lower incomes will not be voluntary members of the group.

In Table 6, the first simulation shows that the value for k must be

extremely high (800) before we reach the number of voluntary contributors (61) identified by positive values of $DEMIT_i$. While high values of k are not inconsistent with the model, ordinarily lower values would be expected. Our simulation results are similar to Andreoni's, who also underpredicted the number of voluntary contributors. The simulation's underprediction may be traced to the specific utility function assumed as well as the assumption of homogeneous taste. More important, the model may be underpredicting, because it does not account for the inducement that trade sanctions, financial assistance, and delayed compliance provided for developing countries. Our underprediction may well mean that these inducements had the intended effect of increasing the number of treaty members. The real effect of this increased membership will not be known until these "Article 5" nations are required to comply.

The second simulation is within the group of nations defined by FREE = 1. A priori, we expected the simulation over this more homogeneous group to provide a better fit to observed behavior. However, we found that the largest number of predicted contributors is 26, while in reality 34 of the 51 made positive contributions. Thus, the simulations based on homothetic preferences appear to underestimate the number of contributors to the public good.

7. A Contrasting Case: Sulfur Dioxide Emissions

The 1979 Convention on Long-Range Transboundary Air Pollution (LRTAP) provides the basis for an additional test of the noncooperative behavior of nations with respect to an international environmental problem. This Convention entered into force on 16 March 1983, but did not provide any explicit targets on reducing sulfur dioxide (SO_2) or other acid-rain-inducing emissions. A subsequent Geneva Protocol on 28 September 1984 set down

guidelines for a cooperative program of financing and evaluating SO_2 and other emissions.[20] On 8 July 1985, a Helsinki Protocol to the LRTAP Convention committed the ratifiers to reducing SO_2 emissions by 30 percent, based on 1980 emission levels, by 1993. While the primary focus of LRTAP was acid rain in Europe and, therefore, placed targets on reducing sulfur emissions, a Sofia Protocol in 1988 to the convention (31 October 1988) added targets for nitrogen oxides emissions. We concentrated on the voluntary contributions of a nation in reducing SO_2 emissions.

Because the SO_2 targets set forth in LRTAP are scheduled to begin in 1993, any reductions prior to 1993 should be viewed as voluntary contributions. By taking the difference in SO_2 emission in 1980 and 1989, we compute the reduction in SO_2 emissions in the 1980s, referred to as DSO2. Emission data come from WRI (1992). The base year is 1980 owing to the Helsinki Protocol. In Table A2 in the appendix, the European nations with positive reductions and their respective incomes are displayed. We excluded the following countries: Albania, Canada, Japan, and the United States, leaving 21 nations with positive reductions. The latter three nations are excluded because their emissions do not add to acid rain within Europe.

The analysis of the cross-national voluntary contributions to SO_2 reductions provides another test of the noncooperative, pure public good theory. In contrast to reductions in CFCs emissions, SO_2 reductions do not uniformly affect the international environment, since acid rain is more localized. The impact on (say) Czechoslovakia of a reduction of SO_2 from (say) France could be completely different when compared to an equal reduction from (say) the United Kingdom, owing to prevailing winds and distance. Rather than contributing to a classic public good, the reductions in SO_2 are contributions to an impure public good. Additionally, reductions in CFCs

generate little, if any, private benefits, while reductions in SO_2 improve local air pollution and generate localized private benefits. Thus, the problem of SO_2 is characterized by impurity and joint products.

Based on a pure public good model, we predict that the voluntary contributions of nations to an international public good should be linearly related to income. This prediction is essentially borne out for CFCs reductions. If we apply this same theory to the reductions in SO_2, we should anticipate that the theory will be rejected. If it is not, we can conclude that the power of the theory to discriminate between problems is very weak, making the theory essentially useless for understanding behavior. By applying the pure public good theory to this problem, we can indirectly test the theory.

Ordinary least squares and nonlinear least squares estimates of the linear and Box-Cox models of DSO2 are presented in Table 7, and are comparable to the estimates presented in Tables 3 and 4. We do not include geographic location dummy variables, because all of the nations fall in the same latitude category. Both models again provide good fits to the data as measured by the R-squares. As expected, the income coefficients are positive and significant. The coefficients on GASTIL are insignificant, probably reflecting the lack of variation in the data with respect to this measure. The primary estimate of interest is that of LAMBDA, the Box-Cox transformation parameter, whose point estimate is 0.577 in Model 1 and 0.589 in Model 2. These estimates are a considerable distance from one. Rather than linear, the underlying relationship is closely approximated by the square root function. This denotes sufficient evidence to reject the pure public good theory; hence, the model does appear to have the power to discriminate between problems.

An obvious next step is to model the provision of the impure public

good. In a different paper (Murdoch and Sandler, 1993), we have built such an impure public good model and, as expected, have found it to predict sulfur emission reductions. For this alternative model, income and GASTIL are significant determinants of reduced emissions. This leads us to conclude that support of the transitional economies and the promotion of political freedoms may have a big payoff in terms of an environmental dividend.

8. Conclusions

Based on the theory of the voluntary provision of pure public goods, we have identified GNP, political freedom, and latitude bands as explanatory variables that determine CFCs emission-reducing behavior in the absence of a cooperative agreement or treaty. Our statistical analysis showed that these variables are correlated with the emission-reducing nations' behavior in the late 1980s. In addition, regressions indicated that the variation in CFCs emission reductions between 1986 and 1989 is, in large part, explained by GNP, political rights, and geographical latitude. A Box-Cox transformation test came close to verifying that a linear relationship between CFCs emission reduction and GNP, as predicted by the theory, is the appropriate relationship. Nations are seen as reducing emissions beyond treaty-mandated levels even prior to the Montreal Protocol taking effect. On average, 61 nations in our data set reduced CFCs emissions by 41.6 percent from 1986 to 1989. This average is in excess of the 20 percent cutback mandated by the Protocol from the year commencing on 1 July 1993. This finding suggests that the initial provisions of the Montreal Protocol is largley consistent with noncooperative cutbacks in CFCs emissions. Because we are unable, owing to data limitations, to test our noncooperative model against a cooperative alternative, such as Lindahl, we cannot conclude that the Montreal Protocol

will not eventually foster cooperation.[21] To perform such a test, we would need a time-series of post-protocol emission cutbacks, which will not be available for some time.

Researchers before us have distinguished the ozone depletion problem from other global commons problems, such as global warming. For example, Barrett (1992, p. 17) argued that "The Montreal Protocol may not have increased global net benefits substantially compared with the noncooperative outcome." Although our research results concur with this view, we have taken a different tack and applied an explicit noncooperative theory of emission reduction to test empirically whether the Montreal Protocol was largely symbolic. A number of policy conclusions follow from our empirical results. First, the Montreal Protocol may be a poor blueprint for other global agreements, especially those involving <u>impure</u> public goods. Each global commons problem has its own pattern of payoffs based on publicness. Ozone depletion is associated with more-certain and more-costly consequences than problems like global warming. These dire consequences appear to motivate actions by the largest polluters. Second, the wealthiest CFCs emitters may be expected to adhere to the Protocol without the need of an enforcement mechanism, because the net benefits from doing so are apparently positive. Self-interests will motivate compliance. Third, an increase in the number of democratic countries is apt to increase the number of nations that will take steps to curb transboundary emissions (also see Congleton, 1991). Thus, increases in the GASTIL indices, achieved after 1989 by the transitional countries of Central and Eastern Europe, may serve to increase compliance with the Protocol's provision. Fourth, foreign aid that increases the GNP level of developing and transitional economies should accelerate the adherence to the mandated reductions in CFCs emissions. An environmental dividend can stem

from foreign aid, because the preservation of environmental assets is a normal good. Fifth, the use of side payments, a deferred adherence schedule, and the threat of trade sanctions may increase the number of participants well beyond the number predicted by the theory. The accomplishment, in terms of ozone protection in the future, from this increase in group size is yet to be known, since many of these countries did not emit CFCs. Sixth, the behavior of European nations with respect to SO_2 emissions did not abide by the predictions of the voluntary provision of a pure public good. Localized benefits and/or cost played a larger role for acid rain and, as such, may necessitate greater side payments to upstream countries such as the United Kingdom.

Footnotes

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1. See Helm (1991) for analyses of a host of global and regional transboundary problems including ozone shield depletion, global warming, tropical deforestation, and acid rain. Also see Runge (1990) and Sandler (1992a, 1992b) on global collective action problems, and Repetto and Gillis (1989) on tropical deforestation.

2. Strategic interactions are investigated in a game theory framework by Barrett (1991, 1992), Carraro and Siniscalco (1992a, 1992b), Hoel (1991), Mäler (1989, 1991), Sandler (1992c), and Ward (1993).

3. On private provision of public goods, see Andreoni (1988), Bergstrom, Blume, and Varian (1986), Cornes and Sandler (1984, 1985, 1986) Ihori (1992), and McGuire (1974).

4. Congleton (1992, p. 419) included GNP per capita in two of the six empirical models in his Table 1, but later dropped the variable, because of concerns that CFCs regulations could affect GNP. Given the small percentage of GNP related to CFCs production and consumption, we chose to ignore any such simultaneity.

5. On the ozone hole and the chemistry of ozone depletion, see Stolarski (1988) and Toon and Turco (1991).

6. The texts of the Vienna Convention, the Montreal Protocol, and the amendments to the Protocol are given in the United Nations Environment Programme (UNEP)(1991).

7. The Protocol entered into force on 1 January 1989 for the following

nations: Canada, Denmark, Egypt, Finland, France, West Germany, Ireland, Italy, Japan, Malta, Mexico, Netherlands, New Zealand, Norway, Spain, Sweden, Switzerland, Uganda, U.K., U.S., and U.S.S.R. For Australia, Austria, Belgium, Burkina Faso, Cameroon, Ghana, Greece, Hungary, Iceland, Jordan, Kenya, Liechtenstein, Luxembourg, Malaysia, Maldives, Nigeria, Panama, Portugal, Singapore, Thailand, Trinidad and Tobago, Tunisia, and Venezuela, the Protocol did not enter into force until later in 1989. Table A1 in the Appendix lists the ratifiers as of May 1993.

8. For a dynamic stock-adjustment model of pollution, see Ko, Lapan, and Sandler (1992) and Nordhaus (1991).

9. This follows from examining total equilibrium contributions, which implies

$$G^* \geqq f_i(w_i + G^*_{-i}) \qquad i = 1, \ldots, n$$

with equality for $g_i^* > 0$. To derive eq. (8), we invert both sides of this equation and add g_i^* to both sides (Andreoni, 1988, p. 60). Eq. (8) then follows from rearrangement and reinterpretation.

10. A cooperative Lindahl model would imply that each nation chooses y_i and g_i to maximize utility subject to its budget constraint and its budget share $S_i = g_i/G$ for the public good. That is, each person faces the following problem:

$$\max_{y_i, g_i} \{U_i(y_i, g_i/S_i; \theta) \mid y_i + pg_i = w_i\}.$$

At a Lindahl equilibrium where the S_is and G are consistent over the contributors, the first-order conditions imply the following demand functions:

$$g_i = g_i(w_i, p, S_i; \theta)$$

for each contributor.

11. Bienen and van der Walle (1989) provided evidence that African

autocracies last only four years on average.

12. According to Olson (1993), an autocrat "will spend money on public goods up to the point where his last dollar of expenditure on public goods generates a dollar's increase in his share of the national income."

13. Simply add g_i^* to both sides of (16), clear fractions, and solve for g_i^* to derive the top part of (17) for positive contributions.

14. If preferences are Cobb-Douglas, so that $U_i = y_i^{1-\alpha}G^{\alpha}$, then $k = [(1 - \alpha)/\alpha]$ as in Andreoni's (1988) simulations.

15. The status of countries with respect to the Montreal Protocol is obtained from the Status of Ratification of the Montreal Protocol (U.N. Environment Programme, 1993), which is updated monthly and contains the dates of when the Protocol was signed, "ratified," and entered into force for each participating nation. Although numerous countries have ratified the Protocol (113 as of June 1993), only 46 are signatories to the document. Technically, only signatory nations can "ratify" the Protocol; however, other policy instruments are defined for formal participation and include Accession, Approval, Acceptance, and Succession. We refer to all nations officially accepting the Protocol as ratifiers, regardless of which policy instrument was used to define participation.

16. See Table A1 in the appendix for a lisitng of the countries where we used the CIA (1989) estimate of GNP85.

17. In cases where the latitude cut through a country's border, we coded the country based on where the largest area is located. We also coded questionable countries both ways and then checked the robustness of the results to the coding change.

18. The equation for the Box-Cox model is DEMIT = 4.366 − .134(6.126)

$- .904(.361) - 1.283(.082) + 2.535((GNP^{.853} - 1)/.853) = 3.073$

$+ 2.535\ ((GNP^{.853} - 1)/.853)$. The equation for the linear model is DEMIT =

$2.712 - .136(6.426) - 1.568(.361) - 1.680(.082) + 1.612(GNP85) = 1.134$

$+ 1.612(GNP85)$.

19. The conversion of the $GNP85_i$ to dollars moves the decimal point 11 spaces to the left, while converting the $DEMIT_i$ to grams moves the decimal point 9 spaces to the right. This gives .01612 as our estimate for $\partial g_i/\partial w_i = 1/p$.

20. The text for the protocols are given in UNEP (1991).

21. An empirical test of the linear version of the Lindahl model, presented in footnote 10, is impossible with cross-sectional data. To see this, augment the model in eq. (19) with a variable measuring S_i, the Lindahl share for nation i. The most obvious measure for S_i is $g_i/\sum_{j=1}^{n} g_j$. Thus, we have

$$g_i = \beta_0 + \beta_1 w_i + \delta(g_i/\sum_{j=1}^{n} g_i) + \epsilon_i,$$

which is nonlinear in the parameters. For this model, a problem arises because the least squares or maximum likelihood estimator for S_i is $\sum_{j=1}^{n} g_j$, so that the model is undefined as g_i cancels out of the equation. A test of the Lindahl model will, evidently, require time-series data and/or some type of instrumental variables estimator.

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Table 1: Variable Descriptions.

Variable	Description
GNP85	Gross National Product in 1985, expressed in hundred millions of dollars.
EMIT86	CFC emissions in 1986, expressed in thousand metric tons.
EMIT89	CFC emissions in 1989, expressed in thousand metric tons.
DEMIT	EMIT86 – EMIT89.
GASTIL	The sum of the Gastil's indices of civil liberties and political freedom.
FREE	Equal to 1 for GASTIL $\leqq$ 4; equal to 2 for 4 < GASTIL $\leqq$ 9; and equal to 3 for GASTIL $\geqq$ 10.
L1	A dummy variable equal to 1 if a country is located above the Tropic of Cancer, and 0 otherwise.
L2	A dummy variable equal to 1 if a country is located between the Tropics of Cancer and Capricorn, and 0 otherwise.
L3	A dummy variable equal to 1 if a country is located below the Tropic of Capricorn, and 0 otherwise.
LAT	Equal to 1 for L1 = 1; equal to 2 for L2 = 1; and equal to 3 for L3 = 1.

Table 2: Descriptive Statistics.

Variable	Mean	Std. dev.	Minimum	Maximum
		Entire Data Set (n = 172)		
GNP85	854	3754	0.345	40128
EMIT86	4.481	18.464	0	197.40
EMIT89	3.369	13.701	0	130.00
DEMIT	1.112	7.030	−37.425	67.40
GASTIL	8.151	4.2770	2	14
FREE	2.186	0.865	1	3
L1	0.343	0.476	0	1
L2	0.605	0.490	0	1
L3	0.052	0.223	0	1
LAT	1.709	0.560	1	3
		Voluntary Contributors (n = 61)		
GNP85	1943	5926	10	40128
EMIT86	11.423	28.998	0.10	197.40
EMIT89	7.158	19.032	0.039	130.00
DEMIT	4.265	10.056	0.023	67.40
GASTIL	6.426	4.129	2	14
FREE	1.852	0.891	1	3
L1	0.557	0.500	0	1
L2	0.361	0.484	0	1
L3	0.082	0.277	0	1
LAT	1.525	0.648	1	3

Table 3: Nonlinear Least Squares Estimates of the Box-Cox Model. (n = 61)

Variable	Model 1	Model 2	Model 3
INTERCEPT	3.160 (9.95)	4.022 (7.72)	4.366 (7.83)
GNP85	2.535 (10.39)	2.493 (10.46)	2.327 (8.98)
GASTIL		− 0.137 (− 2.05)	− 0.134 (− 1.98)
L2			− 0.904 (− 1.40)
L3			− 1.283 (− 1.24)
LAMBDA	0.822 (20.05)	0.828 (20.44)	0.853 (18.76)
R^2	0.95	0.96	0.96

Note: The dependent variable is $DEMIT_i$. Asymptotic t-ratios are in parentheses.

Table 4: Ordinary Least Squares of the Linear Model. (n = 61)

Variable	Model 1	Model 2	Model 3
INTERCEPT	1.061 (3.28)	2.050 (3.61)	2.712 (4.50)
GNP85	1.649 (31.60)	1.643 (32.34)	1.612 (32.19)
GASTIL		− 0.152 (− 2.09)	− 0.136 (− 1.91)
L2			− 1.568 (− 2.47)
L3			− 1.680 (− 1.55)
R^2	0.94	0.95	0.95

Note: The dependent variable is $DEMIT_i$. t-ratios are in parentheses.

Table 5: Spearman Correlation Coefficients between GNP85 and DEMIT for Alternative Classifications of the Data.

	LAT			
FREE	1	2	3	ALL
1	0.898 (0.08) n=20	0.900 (0.164) n=5	**	0.922 (0.04) n=29
2	**	0.533 (0.281) n=9	**	0.503 (0.24) n=12
3	0.891 (0.075) n=11	0.643 (0.283) n=8	**	0.806 (0.10) n=20
All	0.887 (0.05) n=34	0.695 (0.12) n=22	0.700 (0.035) n=5	0.840 (0.10) n=61

Note: Standard Errors are in parentheses.
** Too few observations to make the estimate.

Table 6: Simulations for Alternative Values of k.

Values of k	Simulation 1[a]	Simulation 2[b]
1	2	2
10	4	5
15	7	7
20	8	7
25	9	7
30	9	7
35	9	8
40	11	9
60	17	10
80	19	12
100	20	13
120	24	16
140	27	18
160	28	19
180	32	19
200	34	19
250	38	20
300	39	21
350	41	22
400	44	23
450	48	24
500	49	24
550	51	25
600	52	26
650	53	26
700	56	26
750	58	26
800	61	26
850	62	26
900	63	26
950	63	26
1000	63	26

[a]Simulation 1 includes 172 countries; all countries in data set.

[b]Simulation 2 includes 51 countries; all countries with FREE = 1 (GASTIL ≤ 4) are included.

Note: This income distribution is based on GNP85.

Table 7: Regression Estimates of the DS02 Models. (n = 21)

	OLS		NLS	
Variable	Model 1	Model 2	Model 1	Model 2
INTERCEPT	184.512 (2.25)	277.929 (2.61)	388.738 (6.87)	410.690 (5.37)
GNP85	159.413 (11.05)	166.869 (10.97)	360.411 (7.35)	356.430 (6.86)
GASTIL		− 23.482 (−1.33)		−5.648 (−0.42)
LAMBDA			0.577 (7.02)	0.589 (6.41)
R^2	0.86	0.88	0.94	0.94

Note: The dependent variable is DS02. Asymptotic t-ratios are in parentheses.

Table A1: Countries Ranked by GNP85: DEMIT, Gastil Index, and Ratification Date or Status.

RANK	COUNTRY	GNP85[a]	DEMIT[b]	GASTIL	RATIFY
1	United States	40127760.44	67.4	2	April 21, 1988
2	USSR*	23540400.48	34.4	14	November 10, 1988
3	Japan	13584825.00	-37.4	2	September 30, 1988
4	Germany, Federal Rep.	6707747.38	16.0	3	December 16, 1988
5	France	5379075.00	14.9	3	December 28, 1988
6	United Kingdom	4795544.60	15.5	2	December 16, 1988
7	Italy	4411285.82	15.4	2	December 16, 1988
8	Canada	3588592.01	9.4	2	June 30, 1988
9	China[c]	3432115.53	6.1	12	June 14, 1991
10	Brazil[c]	2263918.80	2.6	5	March 19, 1990
11	India[c]	2218925.95	-3.5	5	June 19, 1992
12	German Democratic Rep.*	2080500.00	4.4	13	January 25, 1989
13	Australia	1831079.60	4.3	2	May 19, 1989
14	Mexico[c]	1711823.20	0.2	8	March 31, 1988
15	Iran, Islamic Rep. of[c]	1680056.00	2.2	11	October 3, 1990
16	Spain	1648784.74	10.7	3	December 16, 1988
17	Czechoslovakia*	1570150.00	-2.2	13	October 1, 1990
18	Romania*	1493033.16	-2.1	14	January 27, 1993
19	Netherlands	1354908.50	3.9	2	December 16, 1988
20	Switzerland	1052994.40	3.4	2	June 29, 1988
21	Saudi Arabia	991372.50	0.5	13	March 1, 1993
22	Sweden	988640.12	0.8	2	June 29, 1988
23	Korea, Rep. of	948393.60	-2.0	9	February 27, 1992
24	Nigeria[c]	946855.58	9.9	12	October 31, 1988
25	Taiwan*	865000.00	0.0	10	Not Ratified
26	Indonesia[c]	856076.00	4.4	11	Not Ratified
27	Belgium	835958.48	2.7	2	December 30, 1988
28	Poland	773822.57	2.0	11	July 13, 1990
29	South Africa	685568.32	-3.8	11	January 15, 1990
30	Austria	683727.59	1.9	2	May 3, 1989
31	Venezuela[c]	656314.68	-0.3	3	February 6, 1989
32	Argentina[c]	649083.61	0.3	4	Not Ratified
33	Norway	599693.20	-0.2	2	June 24, 1988
34	Denmark	578393.40	1.4	2	December 16, 1988
35	Algeria[c]	555980.80	0.0	12	October 20, 1992

Table A1 (cont.)

RANK	COUNTRY	GNP85[a]	DEMIT[b]	GASTIL	RATIFY
36	Turkey[c]	543348.00	3.8	8	September 20, 1991
37	Finland	540861.60	2.1	4	December 23, 1988
38	Yugoslavia[c]	476334.01	0.8	11	January 3, 1991
39	Thailand[c]	413464.06	-0.7	7	July 7, 1989
40	Colombia	383643.00	1.3	5	Not Ratified
41	Greece	358075.94	2.7	4	December 29, 1988
42	Hong Kong	331724.80	0.0	2	December 16, 1988
43	Pakistan[c]	327012.00	-5.9	9	December 18, 1992
44	Philippines[c]	318168.35	-1.3	7	July 17, 1991
45	Iraq*	310011.00	0.7	14	Not Ratified
46	Egypt, Arab Rep. of[c]	309257.00	0.2	8	August 2, 1988
47	Malaysia[c]	308935.40	-1.1	8	August 29, 1989
48	United Arab Emirates	284310.00	0.3	10	July 7, 1989
49	Israel	277684.80	0.3	4	June 30, 1992
50	Kuwait[c]	256286.40	0.4	8	November 23, 1992
51	Libya[c]	248361.60	0.0	12	July 11, 1990
52	New Zealand	219497.20	1.2	2	July 21, 1988
53	Hungary	206745.80	-2.0	10	April 20, 1989
54	Portugal	200092.90	2.7	3	October 17, 1988
55	Peru	195768.40	-0.5	5	March 31, 1993
56	Singapore	194663.80	1.4	9	January 5, 1989
57	Korea, Democratic Rep.*	185503.59	0.0	14	Not Ratified
58	Bulgaria*	182784.02	-0.2	14	November 20, 1990
59	Chile[c]	175754.50	0.9	11	March 26, 1990
60	Ireland	171472.70	1.1	2	December 16, 1988
61	Syrian Arab Rep.[c]	168373.80	-0.6	13	December 12, 1989
62	Puerto Rico	158848.80	0.0	2	April 21, 1988
63	Bangladesh[c]	150889.50	0.0	10	August 2, 1990
64	Morocco	123872.00	-1.3	9	Not Ratified
65	Viet Nam*	122144.24	0.0	14	Not Ratified
66	Ecuador[c]	108784.81	0.7	5	April 30, 1990
67	Guatemala[c]	95556.01	-1.1	8	November 7, 1989
68	Oman	93025.80	0.0	12	Not Ratified
69	Cameroon[c]	85604.40	0.0	13	August 30, 1989
70	Tunisia[c]	84953.71	0.4	10	September 25, 1989
71	Trinidad & Tobago[c]	72048.00	0.2	3	August 28, 1989
72	Sudan	69817.60	0.0	12	January 29, 1993
73	Myanmar	67579.20	0.0	14	Not Ratified
74	Tanzania	66726.00	0.0	12	April 16, 1993
75	Cote d'Ivoire	64587.60	0.5	11	April 5, 1993

Table A1 (cont.)

RANK	COUNTRY	GNP85[a]	DEMIT[b]	GASTIL	RATIFY
76	Kenya[c]	63094.33	−0.3	11	November 9, 1988
77	Sri Lanka[c]	61764.30	−0.2	7	December 15, 1989
78	Jordan[c]	53641.80	−0.8	10	May 31, 1989
79	Zimbabwe[c]	52957.81	0.4	10	November 3, 1992
80	Angola*	52524.01	0.0	14	Not Ratified
81	Yemen Arab Rep.	52503.01	0.0	13	Not Ratified
82	Luxembourg	52008.60	0.1	2	October 17, 1988
83	Qatar	50859.90	0.0	10	Not Ratified
84	Uruguay[c]	50568.00	0.1	4	January 8, 1991
85	Zaire	49139.20	0.0	14	Not Ratified
86	Dominican Rep.	48761.60	0.3	4	Not Ratified
87	Ghana[c]	46694.00	0.6	13	July 24, 1989
88	Ethiopia	46498.11	0.0	14	Not Ratified
89	Panama[c]	45780.00	0.02	9	March 3, 1989
90	Paraguay	43208.10	−0.2	10	December 3, 1992
91	Afghanistan*	39791.42	1.0	14	Not Ratified
92	El Salvador[c]	39574.40	0.2	6	October 2, 1992
93	Brunei	37733.70	0.0	11	Not Ratified
94	Costa Rica[c]	34846.00	0.2	2	July 30, 1991
95	Gabon	33100.40	−0.1	12	Not Ratified
96	Honduras	32434.20	0.1	5	Not Ratified
97	Bahrain*	32064.85	0.04	10	April 27, 1990
98	Nepal	28367.90	0.0	7	Not Ratified
99	Iceland	28100.60	0.05	2	August 29, 1989
100	Uganda[c]	27892.00	0.0	9	September 15, 1988
101	Albania*	27546.60	0.0	14	Not Ratified
102	Cyprus[c]	27372.60	−0.3	6	May 28, 1992
103	Bolivia	26121.10	−0.4	5	Not Ratified
104	Nicaragua	25194.40	0.2	10	March 5, 1993
105	Zambia[c]	24804.80	0.0	10	January 24, 1990
106	Madagascar	24508.80	−0.03	11	Not Ratified
107	Senegal	24297.90	0.4	7	Not Ratified
108	Papua New Guinea[c]	23874.80	0.0	4	October 27, 1992
109	Mozambique	23444.70	0.0	13	Not Ratified
110	Guinea[c]	21581.00	0.0	12	June 25, 1992

Table A1 (cont.)

RANK	COUNTRY	GNP85[a]	DEMIT[b]	GASTIL	RATIFY
111	Jamaica	21024.00	-0.4	5	March 31, 1993
112	Reunion	20802.60	0.0	3	December 28, 1988
113	Bahamas, The	20740.80	0.0	4	Not Ratified
114	Congo, People's Rep.	19970.40	0.0	13	Not Ratified
115	Lebanon*	18409.20	0.0	9	March 31,1993
116	Haiti	18358.20	0.0	13	Not Ratified
117	Macau*	17052.00	0.0	3	October 17, 1988
118	Rwanda	16872.80	-0.01	12	Not Ratified
119	Mongolia*	16790.40	0.0	14	Not Ratified
120	Niger[c]	15338.40	0.0	13	October 9, 1992
121	Martinique	13940.00	0.0	3	December 28, 1988
122	Sierra Leone	13165.20	0.0	10	Not Ratified
123	Malawi[c]	12527.30	0.0	13	January 9, 1991
124	New Caledonia	12178.53	0.0	3	December 28, 1988
125	Guadeloupe*	12124.20	0.0	3	December 28, 1988
126	Namibia*	12115.80	0.0	5	Not Ratified
127	French Polynesia	11952.90	0.0	3	December 28, 1988
128	Barbados[c]	11757.76	0.1	3	October 16, 1992
129	Burundi	11740.00	0.01	13	Not Ratified
130	Malta	11661.00	-0.2	6	December 29, 1988
131	Fiji[c]	11410.00	0.1	4	October 23, 1989
132	Mauritius[c]	11220.00	0.0	4	August 18, 1992
133	Mali	11083.50	0.0	13	Not Ratified
134	Burkina Faso[c]	11033.40	0.0	13	July 20, 1989
135	Benin	10511.80	0.0	14	Not Ratified
136	Yemen, PDR	10471.30	0.0	10	Not Ratified
137	Liberia	10454.40	0.1	10	Not Ratified
138	Bermuda	10281.60	0.0	2	December 16, 1988
139	Suriname	9867.90	-0.02	12	Not Ratified
140	Botswana[c]	9309.00	0.0	5	December 4, 1991
141	Somalia	8614.40	0.0	14	Not Ratified
142	Chad	8028.80	0.0	14	Not Ratified
143	Togo[c]	7291.20	-0.2	12	February 25, 1991
144	Central African Rep.	7232.40	0.0	13	March 29, 1993
145	Mauritania	7064.00	0.0	13	Not Ratified
146	Lao PDR	6792.66	0.0	14	Not Ratified
147	Lesotho	6180.00	0.0	10	Not Ratified
148	Swaziland[c]	4854.50	0.0	11	November 10, 1992
149	Guyana	3792.00	0.0	10	Not Ratified
150	Djibouti*	3745.00	0.0	12	Not Ratified

Table A1 (cont.)

RANK	COUNTRY	GNP85[a]	DEMIT[b]	GASTIL	RATIFY
151	French Guiana*	2648.60	0.0	3	December 28, 1988
152	Belize	1909.00	0.0	2	Not Ratified
153	Antigua & Barbuda	1724.30	0.0	5	December 3, 1992
154	St. Lucia	1710.00	0.0	3	Not Ratified
155	Guinea-Bissau	1683.40	0.0	12	Not Ratified
156	Seychelles	1663.20	0.0	12	January 6, 1993
157	Gambia, The[c]	1570.80	0.0	7	July 25, 1990
158	Bhutan	1543.20	0.0	10	Not Ratified
159	Cape Verde	1438.80	0.0	13	Not Ratified
160	Solomon Islands	1392.30	0.0	5	Not Ratified
161	Equatorial Guinea	1268.20	0.0	14	Not Ratified
162	Vanuatu	1262.24	0.0	6	Not Ratified
163	Comoros	1185.00	0.0	12	Not Ratified
164	Grenada	1123.20	0.0	5	March 31, 1993
165	St. Vincent & the Grena	1061.97	0.0	4	Not Ratified
166	Western Somoa	1010.60	0.0	7	Not Ratified
167	Dominica	920.40	0.0	4	March 31, 1993
168	St. Kitts & Nevis[c]	734.80	0.0	2	August 10, 1992
169	Tonga	708.10	0.0	8	Not Ratified
170	Maldives[c]	512.40	0.0	10	May 16, 1989
171	Kiribati*	363.66	0.0	3	January 7, 1993
172	Sao Tome & Principe	345.60	0.0	14	Not Ratified

[a]GNP85 in 10,000 U.S. dollars.

[b]Rounded for presentation. DEMIT is the difference between CFCs emissions in 1986 and 1989.

[c]Article 5 nations as of December 31 1992 (U.N. Environment Programme, 1993).

Sources: GNP85 is taken from World Bank (1992) except where indicated by an asterisk. GNP85 for countries with an asterisk is taken from CIA (1989). DEMIT is calculated from data in World Resources Institute (1990, 1992). GASTIL is taken from Gastil (1986, Table 1). Ratification dates are from U.N. Environment Programme (1993). (Current Status is available via FAX from Multilateral Fund at 514-282-1122.)

Table A2: SO_2 and Income Data for the Countries Contributing to Reducing SO_2 in the 1980s.

Country	GNP85[a]	DSO2[b]
USSR*	23.5404	3482
Germany, Federal Rep.	6.7077	1700
France	5.3791	1990
United Kingdom	4.7955	1296
Italy	4.4113	1390
Czechoslovakia*	1.5702	300
Netherlands	1.3549	174
Switzerland	1.0530	52
Sweden	.9886	282
Belgium	.8360	414
Poland	.7738	190
Austria	.6837	222
Norway	.5997	68
Denmark	.5784	208
Finland	.5409	266
Greece	.3581	40
Hungary	.2067	416
Portugal	.2001	62
Bulgaria*	.1828	4
Iceland	.1715	72
Luxembourg	.0520	12

[a]GNP85 is in 100 billions of dollars and is taken from World Bank (1992), except where indicated by an asterisk. GNP85 for countries with an asterisk is taken from CIA (1989).

[b]The difference between SO_2 emissions in 1980 and 1989. Positive values indicate a reduction in emissions. DSO2 is completed from data in World Resources Institute (1992).