# WHY COOPERATE? PUBLIC GOODS, ECONOMIC POWER, AND THE MONTREAL PROTOCOL

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*Abstract*—This paper develops a correlated probit model to describe dichotomous choices that may contain a public-goods component or some other forms of interdependency. The key contribution of the paper is to formulate tests for interdependent behavior among agents. In particular, we examine the decisions by nations whether or not to ratify the Montreal Protocol on Substances that Deplete the Ozone Layer. Specifically, we reject free riding as a motive for not ratifying the Protocol, and we find little evidence that individual nations were influenced by the behavior of their largest trading partners. Hence, the data suggest that, with respect to the Montreal Protocol, most nations acted without regard for the actions of other nations.

## I. Introduction

COOPERATION hints at the existence of interdependencies. One agent cooperates with another because it is to its benefit to do so. There are a myriad of reasons why cooperation may be beneficial, including economies of scale, externalities, agglomeration economies, and political realities. Consider, for example, a metropolitan area with serious road congestion. The various communities could each devise a rapid transit system that would be costly and ineffective. An area-wide rapid transit system might be the right solution, but any one community might opt out of such an arrangement. The cost of opting out is greater if more of the area communities join, as that will make it more difficult to attract economic development. As a second example, consider how a particular legislator's vote on a bill could be influenced by her network connections. If her close legislators are more likely to vote yes, then, all else equal, she may well be more likely to vote yes; hence, we would hypothesize a positive network correlation. A third example with a public-goods flavor is the decision to introduce a particular type of tax or to build a public park or entertainment center (such as a sports arena). In this case, the decision may well depend on the existence of similar taxes or facilities in surrounding areas as well as the relationship between the areas. This relationship might be based, in part, on the relative rates of existing taxes, relative property values, or some other interjurisdictional connection.

This paper focuses on an international form of cooperation between nations, namely the Montreal Protocol on Substances That Deplete the Ozone Layer. Interdependence among nations may exist for two reasons. First, the protection of the ozone layer is essentially a pure public good. If a large emitter of ozone-depleting substances (say country A) is likely to ratify the protocol (and, therefore commit to a large reduction in emissions), then another country (say B) may be more likely to not ratify the Protocol and simply take advantage of the protection provided by country A. This free riding means that the ratification decision by one nation is not independent of the ratification decisions of the other nations.[1]

A second reason that we suspect interdependence is the potential for one nation to exert political pressure on another. In this paper, we express this potential through the value of international trade flows. We hypothesize that some country (again, say A) has more influence, or *power,* over another country (say B) the more country B exports to country A, since A can threaten to disrupt the flow of goods that it buys from B through tariffs, quotas, regulatory restrictions, or other means.[2] Thus, if country A is likely to ratify the Protocol, it can increase the likelihood of country B ratifying the Protocol to the extent that B is dependent on A as an export market. Based on 1985 international trade flows, we construct power matrices that capture the hypothesized interdependence for 89 of the largest countries in the world. This is not to say that these power matrices are the only way one might model political interdependence between nations. Alternative indicators might be joint memberships in international alliances, similar voting patterns on past international agreements, foreign aid flows, military security arrangements, oil flows,[3] geographic proximity, and so on. In essence, one might say that the power matrix based on trade flows focuses on economic proximity. For comparison, we also consider power based on geographic proximity, so that countries that are close to each other (for example, share a common border) are hypothesized to exert more influence than those further away; and we consider the effect of alternative definitions of trade.

Econometrically, interdependence between agents may be viewed as an example of spatial correlation (Cliff & Ord, 1973) and network correlation (Milgram, 1967). These concepts have been incorporated in several ways into the ordinary regression model (Anselin, 1988; Cressie, 1993). The dependent variable in the present case—and, as the examples above show, in many other situations—is not continuous but rather dichotomous. Does a nation ratify the Montreal Protocol? The usual empirical model, probit or

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[1] Other decisions may also be interdependent. For example, the decision whether to comply with the treaty after ratification is likely dependent on the behavior of other nations.

[2] For example, in the spring of 1995, the United States wielded power over Japan when it threatened a 100% tariff on luxury automobiles from Japan. Our measure of power suggests that the United States is able to influence the Japanese because the U.S. market is relatively large for the Japanese exporters.

[3] Note that oil flows indicate a reverse power relationship, that is, one where the exporting country has power over the importing country. Thus, OPEC holds a significant international power position.

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logit, cannot handle interdependence between agents. This paper modifies the probit model through the use of recently developed numerical approximation techniques[4] and delivers an estimate of the degree of interdependence that is predicated on the specification of the power measure.

Altogether, our paper makes several contributions. First, our characterization of power via the power matrices provides a blueprint for modeling influence in other problems of interrelated decision-making. Our use of international trade flows and of geographic proximity are primarily examples of how one may operationalize the power matrix. Second, we provide a blueprint for estimating an interdependent probit model, which can be used to analyze other limited-dependent-variable problems that contain interdependent observations (for example, Murdoch, Sandler, and Vijverberg, 2003). Third, our empirical models of the ratification of the Montreal Protocol go well beyond the existing empirical studies (Congleton, 1992). And, fourth, we provide a template for interpreting the marginal effects of the independent variables in a spatial or network correlation probit model.

The remainder of the paper is organized into four sections. In the next section, we present a brief background on the Montreal Protocol. Then, we describe the data and variable definitions within the context of the ordinary and correlated probit models. In section IV, we discuss the results, and their robustness. The last section contains concluding remarks.

## II. The Montreal Protocol

Stolarski and Cicerone (1974) and Molina and Rowland (1974) first suggested that chlorofluorocarbons (CFCs) would reach and destroy the stratospheric ozone shield.[5] When their papers were published, the world production of CFCs was growing substantially, almost 10% per year. Moreover, because the rates of use in India and China were so low compared to the rates in developed nations, forecasts for future CFC production suggested continued growth for the next 30–50 years. Seeing an imminent threat, the U.S. environmental movement widely criticized the use of CFC propellants in aerosol spray cans. Consequently, by 1978, the United States unilaterally banned CFC propellants. Meanwhile, a substantial scientific effort to measure the ozone shield was begun. In 1985, Farman et al. (1985) published their research identifying a hole in the ozone shield over Antarctica.

Two months before the publication of Farman et al., representatives from several nations negotiated the Convention for the Protection of the Ozone Layer in Vienna (the Vienna Convention). This precursor to the Montreal Protocol asked that ratifying nations commit to monitor the ozone layer, exchange scientific information, and develop domestic programs for limiting ozone-depleting substances. In September of 1987, 36 nations signed the Montreal Protocol, which extended the Vienna Convention by setting explicit limits for the emissions of CFCs and some other ozone depleters. Briefly, the Protocol required that:

1. by 1993 ratifiers reduce their annual consumption and production of CFCs to 1986 levels,
2. by 1994 ratifiers reduce their annual consumption and production to 80% of 1986 levels,
3. by 1998 ratifiers reduce their annual consumption and production to 50% of 1986 levels,
4. certain trade restrictions would apply to nonratifying nations, and
5. developing nations would be granted a 10 year delay in meeting the Protocol, as well as financial and technical assistance.

The Protocol entered into force in 1989 after at least 11 nations ratified the document. By January 1, 1990, 44 of the 89 nations in our data set had ratified the protocol (UNEP, 1993).

## III. Ratification as an Interdependent Probit Model

### A. *The Ratification Decision in a Standard Probit Model*

Our goal is to develop an empirical model that explains the ratification choice for individual nations. In this section we develop the conventional probit approach to analyzing this choice. In section IIIB we extend the model to allow for interdependence among nations.

Assuming that each nation assesses the benefits and costs of ratifying the accord, a rational decision-making framework suggests that a nation ratifies the accord only when the perceived benefits outweigh the perceived costs. One may conceptualize the net benefits of ratification either in monetary terms or as the net gain in utility. The exact conceptualization does not matter, because we do not directly observe a nation's net benefits, only its ratification choice. Thus, we hypothesize a model that generates the unobserved net benefits and then estimate the parameters of the model using a limited-dependent-variable estimator.

Let $NB_i$ denote the unobservable or latent net benefits (monetary or utility) of country $i$. The hypothesis is that these net benefits are a function of several observable influences. Let $x_i$ represent a 1-by-$k$ vector of the factors that influence $NB_i$ in country $i$. Also, let $\beta$ denote a $k$-by-1 vector of unknown parameters that identify the relationship between $NB_i$ and $x_i$. With this notation, the hypothesized relationship is

[4] Börsch-Supan and Hajivassiliou (1993); Hajivassiliou, McFadden, and Ruud (1996); Hajivassiliou (1993); Keane (1993, 1994); Vijverberg (1997).

[5] For an excellent review of the science, politics, and economics surrounding the Montreal Protocol see Meadows, Meadows, and Randers (1992). The complete text of the treaty is contained in UNEP (1991).

$$NB_i = x_i\beta + \epsilon_i, \quad (1)$$

where $\epsilon_i$ is an independent, normally distributed random variable with zero mean and constant variance. The specification (1) implies that the expected value of $NB_i$ depends on $x_i$.

Let $y_i = 1$ for nations that ratify the environmental accord and $y_i = 0$ for the nonratifying countries. Then, a rational decision-making framework suggests that $y_i = 1$ for $NB_i > 0$ and $y_i = 0$ for $NB_i \leq 0$. The unknown parameters of equation (1) can be estimated with a standard probit model. A key assumption of the model is that the observations are independent—an assumption that we relax shortly.

For our particular application, the Montreal Protocol, we define *RAT* to equal 1 for nations who ratified the protocol before January 1, 1990. This means that our focus is on *early* ratification of the treaty. As is well known, numerous nations have gone on to ratify the protocol, but these later ratifications suggest a bandwagon effect that is outside of the scope of our behavioral model. Moreover, with the fall of the Berlin Wall, the breakup of the Soviet Union, and the emergence of new nations in eastern Europe, the meaning of ratification is often dubious.

What are the factors that influence $NB_i$? Ideally, each determinant can be identified as contributing to either the costs or the benefits of ratification. Those that increase the costs of ratifying the accord should decrease the probability of ratification, and those that increase the benefits should increase the probability. Furthermore, there may be preference shifters that affect the ratification choice.

In the following sub-subsections, we examine several determinants of costs and benefits. Several variations of these are also discussed in section IVB. Section IIIB describes ways in which the decisions of individual countries may well be interdependent, thus violating the independence assumption behind the probit model. Section IIIC outlines a maximum likelihood estimator that does allow for interdependence.

*The Costs of Compliance:* An obvious measure that seemingly must influence a nation's decision to ratify an accord like the Montreal Protocol is the expected cost of satisfying the targets. As discussed above, the original language in the Protocol requires that ratifying nations achieve 1986 emission rates by July 1, 1993, 80% of 1986 rates by July 1, 1994, and 50% of 1986 rates by July 1, 1999. We therefore suspect that the 1986 emission level (*EMIT*) will influence the cost side of a nation's net benefit of complying with the Protocol. A priori, nations with higher 1986 emission levels would assume greater costs than countries with lower levels, implying that the net benefits of high-emission countries from ratifying the Protocol are lower. On the other hand, nations with low 1986 levels may be anticipating large increases in their emissions. This case is particularly likely for developing nations, which may perceive that ratifying the Protocol is costly even though their current emission rates are low. Thus, the actual effect of *EMIT* on $NB_i$ is confounded.

The situation for the developing nations is explicitly recognized in Article 5 of the Protocol, where they are granted a 10 year extension.[6] To separate the developmental effect from the level-of-emissions effect, we include a binary variable for whether or not a nation is designated a developing nation under Article 5. This variable (*DEV*) will also help to control for the effect that developing nations, by postponing compliance costs through Article 5, may believe that they can reduce future compliance costs as lower-cost substitute compounds emerge over time. The data for *EMIT* were obtained from WRI (1990); the *DEV* data were obtained from UNEP (1993).

*Environmental Quality as a Normal Good:* A nation that ratifies the Protocol can be considered a member of a group of nations that are voluntarily providing a public good. Following Cornes and Sandler (1984) and Bergstrom, Blume, and Varian (1986), we suspect that there is a direct relationship between perceived *NB* and national income. The logic for this argument is simply that with more wealth comes additional demand for environmental quality. However, numerous authors have noted an inverted-U shape of the relation of pollution to income per capita (for example, Barrett and Graddy, 2000); hence, a nonlinear relationship is also possible. To test this relationship, we use a nation's gross national product in 1985 (*GNP*) and the per capita GNP in 1985 (*GNPPC*). Unfortunately, because the use of ozone-depleting substances increases with national income, we know that it will be difficult to sort out the effects of *EMIT* and income. For the majority of the nations in our sample, *GNPPC* was obtained from World Bank (1990). For some nonmarket-economy nations, the data were taken from CIA (1989).[7]

*Geographic Location:* There are two reasons that the geographic location of a nation may influence the net benefits of ratifying the Protocol. First, there is some evidence that the ozone shield thins more at the higher latitudes, especially in the springtime. Hence, nations closer to the poles may see more private (within-country) benefits from protecting the ozone layer and, all else equal, be more likely to ratify the Protocol. Second, international debates are often summarized as north-south debates. A northern

[6] In 1990, the developing nations were provided additional incentives to ratify the protocol in the form of funds to facilitate technology transfers and other projects to reduce the production and consumption of ozone-depleting substances.

[7] A listing of all nations and the source of the GNP data is presented in Sandler and Murdoch (1994).

nation is assumed to have political objectives that are similar to other northern nations, and likewise for southern nations. To control for these effects, we classified the nations into three groups according to geographic location. The first group contains the nations located at or above the Tropic of Cancer, the second group contains the nations located between the Tropics of Cancer and Capricorn, and the third contains the nations at or below the Tropic of Capricorn. We originally used three binary variables to model the groups. However, we found no statistical difference between the second and third groups. Thus, we combined them. The variable *NORTH* is a binary variable that is equal to one for the nations at or above the Tropic of Cancer and equal to zero for the other nations. The classification was based on the maps in Cleveland (1992).

*Form of Government:* Olson (1993) examined the relationship between form of government (dictatorship versus democracy) and development. Olson suggested that autocrats desire to maximize tax revenues, thereby increasing their share of the national income. Given this, we might expect that autocrats are less likely to perceive positive net benefits from ratifying the Montreal Protocol, to the extent that the targets of the Protocol do not augment taxable income. Olson also suggested that dictatorships are "susceptible to succession crises and uncertainty about the future," making them less interested in long-term investments such as reducing ozone-depleting substances.

Congleton (1992) directly addressed the relationship between form of government and pollution control. A more recent empirical look at this question is Barrett and Graddy (2000). Like Olson, Congleton suggested that dictators make decisions over relatively short time horizons. Additionally, authoritarian regimes are less risk-averse and face a higher relative price for pollution abatement than a median voter. Because the preferences of the median voter are represented in democratic regimes, it follows that the authoritarian form of government is less likely to favor an international global environmental accord than a democracy.

Following the analyses of Olson and Congleton, we hypothesize that nations with more democratic forms of government will perceive greater *NB* from ratifying the Montreal Protocol. Thus, we include a variable indicating the form of government as a preference shifter. To measure this variable, we use the indices of civil liberty and political freedom constructed by Gastil (1988). Each measure is an index from 1 to 7 with lower numbers reflecting greater liberties and freedoms. We classify a nation as free ($FREE = 1$) if the sum the civil-liberty and political-freedom indices is 4 or less, and not free ($FREE = 0$) if the sum is 5 or greater.

For reference, variable names, brief descriptions, and summary statistics are presented in table 1.

TABLE 1.—VARIABLE NAMES, DESCRIPTIONS, AND SUMMARY STATISTICS

| Variable | Description | Mean | Std. Dev. |
|---|---|---|---|
| *RAT* | Dummy variable equal to 1 for the nations that ratified the Montreal Protocol by January 1, 1990 and equal to 0 otherwise | 0.49 | 0.50 |
| *FREE* | Dummy variable equal to 1 for the nations where the sum of Gastil's 1985 index of civil liberties and index of political freedoms is less than 5; 0 otherwise | 0.35 | 0.48 |
| *DEV* | Dummy variable equal to 1 for the Article 5 developing nations; 0 otherwise | 0.39 | 0.49 |
| *NORTH* | Dummy variable equal to 1 for the nations at or above the Tropic of Cancer; 0 otherwise | 0.49 | 0.50 |
| *GNPPC* | 1985 gross national product per capita ($/10) | 457.71 | 985.63 |
| *EMIT* | 1986 CFC emissions (000 tons) | 8.63 | 25.03 |

### B. *Interdependence*

*International Power:* Although we recognize that the international community is made up of numerous sovereign, judicially independent nations, we also recognize that the nations are economically interdependent, because of international trade. This interdependence is especially important in a model where the choice variable, the ratification of an international treaty, is inherently political. In particular, where the interdependence is strong, we may observe a country signing a treaty where the pure within-country benefits are negative but the positive political benefits, derived from the interdependence, lead to an overall positive net benefit. We hypothesize that the existence of international trade gives nations political and economic power over other nations and that this power may influence the decision to ratify (or not ratify) international environmental agreements. But how can we measure power? Our approach is to define one nation's (A's) power over another (B) as the product of a measure of A's preference about the issue at hand (ratification of the Protocol) and a power weight index that is related to the magnitude of B's exports to A. In the exertion of power, the direction of the trade is crucial. If, for example, nation B exports a lot to nation A, we then would anticipate that A maintains some power over B, because A could tax or otherwise disrupt the flow of exports, hence harming B.

An example of our calculations of the power weight matrices is presented in tables 2 and 3. In table 2, we show the 1985 exports of three nations (the United States, Canada, and Japan) to each of these nations and the 1985 GNP

TABLE 2.—EXAMPLE EXPORT MATRIX

| Exporting Nation | Importing Nation U.S. | Canada | Japan | Total Exports | GNP |
|---|---|---|---|---|---|
| U.S. | 0 | 47,251 | 22,631 | 69,882 | 4,012,776 |
| Canada | 68,283 | 0 | 4,222 | 72,505 | 358,859 |
| Japan | 66,684 | 4,559 | 0 | 71,233 | 1,358,483 |

Unit = Millions of U.S. dollars per year.

TABLE 3.—EXAMPLE POWER WEIGHT MATRICES

| | $P_1$ | | | $P_2$ | | |
|---|---|---|---|---|---|---|
| | U.S. | Canada | Japan | U.S. | Canada | Japan |
| U.S. | 0 | 0.68 | 0.32 | 0 | 0.01 | 0.006 |
| Canada | 0.94 | 0 | 0.06 | 0.19 | 0 | 0.01 |
| Japan | 0.93 | 0.07 | 0 | 0.05 | 0.003 | 0 |

of each. Thus, we see that Japan exported $66,684 million to the US and $4,559 million to Canada. (The total figures are just for this example, and for purposes of the example we assume that there are only these three nations in the world.) Based on these figures, we develop two power weight indices for each nation. As an example of the first calculation, consider Japan's power over Canada. We see that Canada exports $4,222 million to Japan. This is 0.06, or 6%, of Canada's total exports. Thus, for the first weight index we assign 0.06 to Japan over Canada. The Japanese weight index over the United States is much greater: approximately 0.32 (22,631/69,882) of U.S. exports flow to Japan. The United States is assigned the greatest power weights because, in this example, Japan and Canada export large fractions (0.93 and 0.94, respectively) of their totals to the United States. Each of these weights is displayed the left panel of table 2.

On the right-hand side of table 3, we display a second power weight index ($P_2$). This index is computed in a similar fashion except that the denominator in each index is the exporting nation's GNP. The second index highlights the fact that for some nations (e.g., the United States) exports are a small fraction of total GNP, compared to others (e.g., Japan).

Note that with the full data set, both $P_1$ and $P_2$ are 89 × 89 matrices. The row position denotes the exporting nation, whereas the column position denotes the receiving nation. $P_1$ is derived from the (89 × 89) export matrix by dividing each row by the row total. Thus, the row figures in $P_1$ add up to 1. $P_2$ is computed from the export matrix by dividing each row by that row country's GNP. The row figures of $P_2$ add up to the share of the nation's exports in its GNP. This ratio is a common measure of openness of the nation.

We must emphasize the interpretation of the matrices $P_1$ and $P_2$. When viewed from the row country's point of view, a high power weight index means that the column nation has international economic power over it. The key difference between the two matrices is that $P_2$ includes the importance of the international sector to that country. Using $P_2$ as the power weight matrix implies that the more open nations will necessarily be subjected to greater power influences exerted by other nations.

The matrices $P_1$ and $P_2$ enable us to construct two variables, called $POWER_1$ and $POWER_2$, as measures of the influence of economic interdependence on the net benefits of ratifying the Montreal Protocol. We expect that, all else equal, the net benefits of ratification for some country $i$ will increase as the ratification benefits increase in the countries with economic power over $i$; that is, we expect to find positive network correlation. To see this, consider the example $P_1$ presented in table 3. If the United States perceived large net benefits from the Protocol, then Japan should perceive positive net benefits from ratification, owing to the influence of the United States over Japan. This *partial effect* results from the political benefits Japan receives from voting with an important trading partner. As another example, assume that the United States perceived substantial negative net benefits from the Protocol, while Canada expected large positive net benefits. Then, we would anticipate that Japan would be more influenced by the United States, because the weight is much greater and be more likely to fail to ratify the Protocol.

The actual calculation of $POWER_1$ and $POWER_2$ is easiest to explain with matrix notation. Let $NB$ denote the $n \times 1$ vector of net benefits. Then, with $P_1$ and $P_2$ of dimension $n \times n$, we have

$$POWER_1 = P_1 \cdot NB, \tag{2}$$

$$POWER_2 = P_2 \cdot NB. \tag{3}$$

With the example $P_1$ matrix presented in table 2, $POWER_1$ is

$$\begin{pmatrix} 0 & 0.68 & 0.32 \\ 0.94 & 0 & 0.06 \\ 0.93 & 0.07 & 0 \end{pmatrix} \begin{pmatrix} NB_{us} \\ NB_{ca} \\ NB_{ja} \end{pmatrix} = \begin{pmatrix} 0.68NB_{ca} + 0.32NB_{ja} \\ 0.94NB_{us} + 0.06NB_{ja} \\ 0.93NB_{us} + 0.07NB_{ca} \end{pmatrix}.$$

Thus, for country $i$, $POWER_1$ is simply the weighted average of the net benefits from all other nations where the weights are determined by the trade flows. The calculation is similar for $POWER_2$ except that the weights do not sum to 1. The data to construct the $POWER$ matrices was obtained from IMF (1989) and reflects 1985 trade flows.

*Ozone-Layer Protection is a Public Good:* To the extent that the ratification decision commits a nation to reducing ozone-depleting substances, when one nation ratifies the Protocol, the benefits from its ozone-layer protection spill over to other nations. This means that nations may increase their welfare by acting strategically. In order to measure this type of interdependence, we developed another weight matrix that is based on the 1986 emissions. Let $S$ represent the

$89 \times 89$ matrix and $E$ the total emission in the world in 1986. Then a typical element of $S$ is

$$s_{ij} = \begin{cases} EMIT_j/E & \text{for } i \neq j, \\ 0 & \text{for } i = j. \end{cases} \tag{4}$$

Define $SPILL_i = \sum_{j \neq i}^{89} s_{ij} \cdot NB_j = S \cdot NB$ as the measure of the spillovers to country $i$ from the likely protection from the other nations. Nations with higher emissions get greater weight: because they are required to reduce emissions the most if they ratify, their feelings about ratification of the Protocol matter more in the ratification decision of country $i$.[8] Hence, a negative sign on the $SPILL$ measure would not be inconsistent with free-riding behavior.

### C. *The Interdependent Probit Model*

With the addition of the $POWER$ and $SPILL$ measures, the independence assumption of the simple probit model is violated. To see this, rewrite equation (1) in matrix notation and include (say) equation (2); i.e.,

$$NB = X \cdot \beta + \alpha P_1 \cdot NB + \epsilon, \tag{5}$$

where $X$ is an $(n \times k)$ matrix of factors explaining the level of net benefits, $P_1 \cdot NB$ represents the international influence variable ($POWER_1$) discussed above, $\beta$ is a $(k \times 1)$ vector of parameters, $\alpha$ is a parameter indicating the strength of the power effect, and $\epsilon$ is an $(n \times 1)$ vector of random disturbances that affect the net benefits of ratification but are not captured by the measured explanatory factors. $\epsilon$ is assumed to be identically and independently normally distributed; that is, $\epsilon \sim N(0, I)$.[9]

Equation (5) is not estimable with ordinary probit, because on the right-hand side we have $NB$, which is endogenous and only partially observable. Solving equation (5) for $NB$ yields

$$NB = (I - \alpha P_1)^{-1} X\beta + \epsilon^*, \tag{6}$$

where $\epsilon^* = (I - \alpha P_1)^{-1}\epsilon$ is distributed $N(0, \Omega)$ with $\Omega = (I - \alpha P_1)^{-1}[(I - \alpha P_1)^{-1}]'$. The disturbance term is now correlated.

To estimate this model, recall that a nation ratifies ($y_i = 1$) if $NB_i > 0$ and does not ratify ($y_i = 0$) if $NB_i \leq 0$. Thus, defining $\epsilon^{**}$ in the process,[10] we have

$$y_i = \begin{cases} 1 & \text{iff } \epsilon_i^* > -[(I - \alpha P_1)^{-1} X\beta]_i \\ & \text{or } (1 - 2y_i)\epsilon_i^* = \epsilon_i^{**} < -(1 - 2y_i) \\ & \quad \times [(I - \alpha P_1)^{-1} X\beta]_i = z_i, \\ 0 & \text{iff } (1 - 2y_i)\epsilon_i^* = \epsilon_i^{**} \leq -(1 - 2y_i) \\ & \quad \times [(I - \alpha P_1)^{-1} X\beta]_i = z_i. \end{cases} \tag{7}$$

Define the matrix $\Theta = \{\theta_{ij}\}$ by $\theta_{ij} = 1 - 2y_i$ for $i = j$ and $= 0$ for $i \neq j$. Then $\epsilon^{**} = \Theta\epsilon$, and the vector $NB$ of net benefits translates into the vector $Y$ of ratification decisions on the basis of the inequality $\epsilon^{**} < \Theta(I - \alpha P_1)^{-1} X\beta = Z$. The log-likelihood function is therefore

$$\ln L = \ln \int_{\infty}^{Z} \phi_n(\epsilon^{**}; 0, \Theta\Omega\Theta)\, d\epsilon^{**}, \tag{8}$$

which is the natural logarithm of a single $n$-dimensional normal probability, rather than the sum of $n$ logarithms of one-dimensional normal probabilities as is the case with the customary uncorrelated probit model. The simulation algorithm used to approximate the normal probability is outlined in the appendix.

## IV. Empirical Results

### A. *Benchmark Results*

The results from both the ordinary and correlated probits are given in tables 4 and 5. Three correlated probit models are presented that vary by the type of interdependence. The first includes just the $POWER_2$ measure, the second includes just the spillover measure, and the third includes both sources of interdependence. The models are estimated with $EMIT$ (table 5) and without $EMIT$ (table 4) in order to examine the robustness of the results, given that this variable may depend on $GNP$. Estimates from the models with $POWER_1$ are essentially the same and are available upon request.

The ordinary probit estimates are generally consistent with our expectations and prior research by Congleton (1992) and Beron, Murdoch, and Shukla (1996). The inclusion of $EMIT$, itself never significant, removes statistical significance from the geographic variable $NORTH$ and increases the statistical significance of developing-nations binary variable $DEV$. This latter effect is consistent with

[8] On theoretical grounds one might wish to make the ratification decision of country $i$ dependent on the ratification *outcomes* of other countries, that is, on $y_j$ instead of $NB_j$ for $j \neq i$. Such a model is not estimable. In terms of equation (5), $\epsilon$ is an $n$-dimensional disturbance in $\Re^n$. Each point in $\Re^n$ must be associated with a potential ratification outcome across countries. This requirement of the probit model is violated if $y$ is among the right-side variables of equation (5). For this reason, we model $SPILL$ as a function of $NB$.

[9] The variances are standardized in order to normalize the estimates of the equation's parameters—the variances are not separately identified. The distribution assumption also assumes zero correlations. In principle, one can add parsimonious correlation structures to the model and estimate them. We experimented with $\epsilon = \rho P_1 \epsilon + \mu$ with $\mu \sim N(0, I)$. In this case, random international ratification preferences propagate themselves according to the power weights matrix relationships. This error structure yields $\epsilon \sim N(0, Q_1)$ where $Q_1 = (I - \rho P_1)^{-1}[(I - \rho P_1)^{-1}]'$. But, when estimated, $\rho$ was never statistically significant, unless, under some exploratory variable configurations, the power term ($\alpha P_1 \cdot NB$) was omitted. This shows that (a) in such cases $\rho$ indeed represents omitted determinants, and (b) there is no need to consider a correlated structure once we have allowed for the international influences via our power variable.

[10] Using $y_i$ in the inequality seems to make the two sides of the "if and only if" statement in (7) circular. But it is only a notational device in order to formulate an upper bound on $\epsilon_i^{**}$ for all $i = 1, \ldots, n$.

TABLE 4.—ESTIMATES OF THE ORDINARY PROBIT AND CORRELATED PROBIT MODELS

| Variable | Ordinary Probit | Correlated Probit | | | |
|---|---|---|---|---|---|
| | | Spillover | $POWER_2$ | Combined | Contiguity |
| *GNPPC* | 0.0098 | 0.0098 | 0.0092 | 0.0090 | 0.0101 |
| | (2.38) | (2.38) | (2.24) | (2.19) | (2.50) |
| *FREE* | 1.0090 | 1.0083 | 0.9554 | 0.9433 | 0.9447 |
| | (2.95) | (2.86) | (2.66) | (2.62) | (2.69) |
| *DEV* | 0.5762 | 0.5766 | 0.6873 | 0.7037 | 0.7049 |
| | (1.72) | (1.72) | (1.96) | (1.99) | (1.94) |
| *NORTH* | 0.5309 | 0.5306 | 0.6291 | 0.6402 | 0.3810 |
| | (1.61) | (1.61) | (1.86) | (1.89) | (1.19) |
| *CONSTANT* | −1.280 | −1.157 | −1.556 | −1.273 | −1.2278 |
| | (3.69) | (1.45) | (3.68) | (1.68) | (−3.50) |
| $\alpha_{POWER_2}$ | | | 1.0823 | 1.2277 | |
| | | | (1.13) | (1.21) | |
| $\alpha_{SPILL}$ | | −0.1034 | | −0.3007 | |
| | | (0.18) | | (0.47) | |
| $\alpha_{CONTIGUITY}$ | | | | | 0.3848 |
| | | | | | (1.59) |
| Log likelihood | −45.63 | −45.61 | −44.89 | −44.75 | −44.19 |

Absolute value of the asymptotic $t$-ratio in parentheses.

our argument that income and emissions are linked, whereas the former effect suggests that the northern nations produced greater amounts of emissions in 1985 than did the other nations of the world. According to the parameter estimates of *FREE*, countries with greater civil liberties and political freedoms are more likely to ratify.

The simulated estimates from the $POWER_2$ models generally agree with the estimates obtained from the ordinary probit. The estimate on $\alpha_{POWER_2}$ is positive in all four specifications, but never significant. The positive sign suggests that there may be positive network correlations, but the imprecision of the estimates probably reflects the

TABLE 5.—ESTIMATES OF THE ORDINARY PROBIT AND CORRELATED PROBIT MODELS WITH *EMIT*

| Variable | Ordinary Probit | Correlated Probit | | | |
|---|---|---|---|---|---|
| | | Spillover | $POWER_2$ | Combined | Contiguity |
| *GNPPC* | 0.0084 | 0.0084 | 0.0079 | 0.0079 | 0.0087 |
| | (2.03) | (2.03) | (1.92) | (1.92) | (2.12) |
| *EMIT* | 0.0319 | 0.0318 | 0.0302 | 0.0295 | 0.0179 |
| | (1.13) | (1.13) | (1.04) | (1.01) | (1.24) |
| *FREE* | 0.9392 | 0.9391 | 0.8871 | 0.8867 | 0.9236 |
| | (2.57) | (2.57) | (2.40) | (2.40) | (2.62) |
| *DEV* | 0.6127 | 0.6218 | 0.6981 | 0.6990 | 0.6983 |
| | (1.82) | (1.82) | (1.99) | (1.99) | (1.95) |
| *NORTH* | 0.3951 | 0.3952 | 0.5414 | 0.5453 | 0.2944 |
| | (1.16) | (1.16) | (1.48) | (1.48) | (0.90) |
| *CONSTANT* | −1.299 | −1.167 | −1.577 | −1.364 | −1.2444 |
| | (3.71) | (0.69) | (3.51) | (0.93) | (3.52) |
| $\alpha_{POWER_2}$ | | | 0.4169 | 0.4231 | |
| | | | (0.82) | (0.81) | |
| $\alpha_{SPILL}$ | | −0.0406 | | −0.0725 | |
| | | (0.08) | | (0.15) | |
| $\alpha_{CONTIGUITY}$ | | | | | 0.3129 |
| | | | | | (1.39) |
| Log likelihood | −44.14 | −44.14 | −43.58 | −43.57 | −43.13 |

Absolute value of the asymptotic $t$-ratio in parentheses.

opposing influences captured by the international trade data. The lack of significance of $\alpha$ is nevertheless an important result: whereas one might well speculate that power relations exist in the ratification of international treaties, we have given an economic framework to the power relations and we find with a sophisticated test that, in the context of the Montreal Protocol, the power relations based on international trade seem to play a limited role.

The estimates for $\alpha_{SPILL}$, while always having the anticipated sign, are statistically insignificant, suggesting that the free riding motive is limited in this particular case. This finding is consistent with Murdoch and Sandler (1997) who found that a model of voluntary *independent* behavior was consistent with the emissions reductions from 1986 to 1989.

### B. *Robustness and Sensitivity*

One might suspect that these estimates are dependent on the precise nature of the selected model specification. This section explores how sensitive the results are to variations of various kinds. We can group these specification checks as (1) introducing different variables into the original model, (2) using alternative weights matrices with the data we have used so far, and (3) using a different data source with different countries as well as the alternative weights matrices and varying variable groups.

We begin with a slight modification of our original model using the previously described data. We replace the simple dummy variable *NORTH* in our model by specifying geographical location with the latitude of the country's geographical center. The idea is that latitude, as a continuous measure, might capture proximity to the poles better. The results do not bear this out: in the various models the $t$-statistics are no higher than 0.65 and vary in sign.

Again using the original data and weights matrix we examined a specification with quadratic terms to represent ideas about environmental Kuznets effects. Adding the squared value of GNP per capita in the original model yielded insignificant estimates on both the linear and the quadratic term, in contrast to the significant linear parameter in the benchmark specification.

Next we turned to various redefinitions of the weight matrix, where we step away from the notions of economic power and explore other interaction mechanisms. One such mechanism might be constructed on the basis of military alliances. A cursory check shows a myriad of alliances, each with its own set of conditions and degrees of interaction. It is beyond the scope of this paper to extricate a military-based power matrix. A more straightforward interaction mechanism focuses on contiguity: neighboring countries may well influence each other. The definition of what constitutes a neighbor is less clear: should one share a border, should one live within a certain distance of each other? We explore both of these definitions, using data from Gleditsch and Ward (2000). The last columns of tables 4 and 5 contain the estimates based on the contiguity matrix, constructed by inserting a value of 1 into cell $(i, j)$ if observations $i$ and $j$ share a border and then row-standardizing this matrix. The values of $\alpha$ are 0.38 and 0.31, with the former almost significant at the 5% level in a one-tailed test. A neighbors matrix based on a nearest-border-to-nearest-border distance of 400 kilometers does not yield a statistically significant estimate of $\alpha$ ($t \leq 0.16$). On the one hand, these results suggest that the correlated probit technique is able to yield significant estimates of the interaction parameter, but on the other, geographical contiguity does not clarify whether the interactions are economic or rather political in nature.

We consider, again, the weights matrix based on international trade. Although the *POWER* matrices we used above incorporate the total value of exports, one might argue that one ought to focus on trade in raw materials (because of countries' dependence on them), or on intermediate goods (because the corporate sector has significant economic power), or on final goods (because foreign imports are visible to consumers, who are a major political constituency). At present, such detailed data exist only for a few industrial countries, leaving this avenue of research open should additional data become available in the future.

To detect how sensitive the results are to our definition of trade, we reestimate our original model using several weights matrices based on alternative definitions of international trade. For this we use the World Trade Database (WTDB) bilateral trade flow data amassed by Statistics Canada (Feenstra, Lipsey, & Bowen, 1997). We utilize the augmented WTDB, under their liberal classification scheme, constructed by Feenstra, Markusen, and Rose (2001), that separates trade flows into the categories first suggested by Rauch (1999). The three trade matrices used are based on whether products are traded in an organized exchange (homogeneous), trade is not in an organized exchange but based on some known reference price (referenced), or neither of these two conditions is met (differentiated).

These three types of exports, as well as the sum of them as a measure of total exports, are used to construct new $POWER_1$ and $POWER_2$ matrices. The models of tables 4 and 5 are therefore reestimated with eight different power matrices on the original data, though the number of countries is reduced from 89 to 86 due to three countries not being part of the Feenstra data. With both model specifications, seven of these yield insignificant $\alpha_{POWER}$ estimates, with $t$-values between $-0.73$ and 1.16. Curiously, one power matrix based on differentiated exports as a share of GDP generated a larger $\alpha_{POWER_2}$ with a $t$-statistic of 3.16 and 3.54 respectively. Although this confirms the notions of economic power being played out in the ratification process that we have hypothesized in section III of this paper, we are nevertheless skeptical of this result. With other power matrices and, as discussed below, an alternative data set, there

is no evidence of a statistically significant power effect.[11] Unless we believe that differentiated exports matter in the global power relationships and the other types of exports do not, we must treat this lone estimate as a fluke.

As an additional robustness check we construct a different data set derived from alternative sources. We use World Bank (2000) data for the income and population measures, updates from the United Nations Environmental Programme, Ozone Secretariat, for the ratification (UNEP, 2001) and emissions (UNEP, 1999) measures, and the same sources for all additional countries' other variables of interest. This alternative data set is not a simple expansion of the original one; in particular, 17 countries were lost and 31 were added. Many of the additions are African and Caribbean countries. The change in the countries is due to using the bulk of the available Feenstra data that were originally collected to focus on international flows and not environmental issues. Using these Feenstra trade matrices, the $\alpha_{POWER}$ estimates are never significant ($-1.56 \leq t \leq 0.77$) and are negative more often than not. The $\alpha_{CONTIGUITY}$ estimates are also insignificant ($0.38 \leq t \leq 0.88$), which either confirms our ideas about the weakness of the data or else weakens the contiguity effects estimated on the original data.[12]

As one last sensitivity check we augment the new data with additional variables that might capture different facets of the choice mechanism. In the benchmark model, *EMIT* captures compliance costs. One might also specify the compliance costs in relative terms: define *COMPCOST* as the ratio of *EMIT* to GDP, so that one country with the same emissions but a larger domestic economy would be better able to bear the cost of ratification. One would expect a negative sign on *COMPCOST*. The various models estimated with the new data yield positive estimates with $t$-values around 0.85. Including *EMIT* by itself yields estimates comparable to those in table 5. Therefore, this modification in the specification does not yield any different results either. Adding *COMPCOST* squared to the empirical model with the new data also led to two insignificant estimates.

The wide variety of specification checks we have engaged in suggests that our original specification remains an acceptable model for continued analysis. We turn now to the interpretation of our results.

[11] It might be that the likelihood function exhibits local maxima that hide the existence of a global maximum at a location where $\alpha_{POWER}$ is large and statistically significant, but extensive grid searches have not revealed any such occurrence in practice.

[12] These models were estimated with the latitude variable that measures geographical center. Curiously, this variable drew a negative parameter estimate with a $t$-value of slightly over 2, suggesting that countries closer to the poles would be less likely to ratify. At the same time, the parameter on GNP per capita increased nearly tenfold in size. High multicollinearity is to blame: latitude, GNP per capita, and ratification are all highly positively correlated. Latitude itself is positively associated with ratification, and its effect is difficult to separate from that of income.

### C. *Interpretation*

Although the imprecision of the estimates of $\alpha$ limits the interpretation of the parameters, we can still use one of the estimated network correlation models to demonstrate how the interpretation of these models differs from ordinary probit models. As is clear from equation (1), a given change $\Delta x_{mi}$ in any one exogenous variable $x_m$ ($1 \leq m \leq k$) for country $i$ has a direct influence on the net benefits of ratification; that is, $\Delta NB_i = \beta_m \Delta x_{mi}$. It pays to express this in matrix notation. Define $\Delta X_m^{(i)}$ as an $(n \times 1)$ vector with zero-valued elements for all but the $i^{\text{th}}$ country, and define $\Delta NB^{(i)} = \beta_m \Delta X_m^{(i)}$ as the world's direct effect. For all but the $i^{\text{th}}$ country, the direct effect is zero. Now consider equation (6). What happens in one country affects the other countries, by an amount equal to $\Delta NB^{[1]} = \alpha P_1 \Delta NB^{(i)}$ initially. (From the definition of $P_1$, it follows that the $i^{\text{th}}$ element of $\Delta NB^{[1]}$ is 0.) This response in turn has an impact on the $i^{\text{th}}$ and every other country: $\Delta NB^{[2]} = \alpha P_1 \Delta NB^{[1]}$. The feedback continues, echoing back and forth until the total change in net benefits throughout the world equals $\Delta NB = \beta_m (I - \alpha P_1)^{-1} \Delta X_m^{(i)}$. Consequently, the indirect response, which owes entirely to the international power relationship, equals $\Delta NB - \Delta NB^{(i)} = \beta_m [(I - \alpha P_1)^{-1} - I] \Delta X_m^{(i)}$.

Moreover, as this holds for every variable $x_m$, let us refer to $(I - \alpha P_1)^{-1}$ as the impact matrix. We can get an impression of the international power effect by (a) examining the diagonal elements of the impact matrix to see whether the own total impact differs to any substantial degree from the own direct impact (unity), and (b) examining the off-diagonal elements of the impact matrix to see whether any country has a substantial impact on another.

First, the own total impact is based on the direct impact and on the feedback from a change in a country's behavior that leads other countries to change their behavior and that ultimately affects the first country. For example, when there is a change in the United States's GNP, this leads to a change in its net benefits. This change in the United States's net benefits then affects the behavior of other countries according to the power weights between each country and the United States. This change in other countries' behavior in turn influences the United States's net benefits through their relationship with the United States. Because this secondary effect on the United States's net benefits will then affect, again, other countries, the own total indirect impact captures the total impact after all feedbacks have been taken into account. We denote this total own indirect impact of country $i$ on itself by $\gamma_{ii}$.

Table 6 gives the submatrix from our data set of $(I - \alpha P_1)^{-1}$ for the G7 countries, as well as the USSR, China, India, and Singapore. These results are based on our second power weights matrix and the regression omitting emissions (the third column of table 4). Along the main diagonal we find the elements corresponding to the total impacts (1 +

TABLE 6.—SELECTED NETWORK INTERACTIONS

| Country | U.S. | Canada | U.K. | France | Germany | Italy | USSR | Japan | Singapore | China | India |
|---|---|---|---|---|---|---|---|---|---|---|---|
| U.S. | 1.00514 | 0.01300 | 0.00398 | 0.00383 | 0.00262 | 0.00183 | 0.00089 | 0.00707 | 0.00113 | 0.00125 | 0.00060 |
| Canada | 0.20949 | 1.00292 | 0.00697 | 0.00501 | 0.00321 | 0.00216 | 0.00392 | 0.01487 | 0.00069 | 0.00330 | 0.00137 |
| U.K. | 0.04329 | 0.00638 | 1.00851 | 0.03674 | 0.02970 | 0.01442 | 0.00286 | 0.00595 | 0.00240 | 0.00182 | 0.00327 |
| France | 0.04125 | 0.00455 | 0.03363 | 1.01631 | 0.04455 | 0.02865 | 0.00805 | 0.00737 | 0.00195 | 0.00441 | 0.00270 |
| Germany | 0.02425 | 0.00311 | 0.02135 | 0.03793 | 1.00751 | 0.02504 | 0.00496 | 0.00446 | 0.00139 | 0.00215 | 0.00181 |
| Italy | 0.03004 | 0.00336 | 0.01765 | 0.03769 | 0.03193 | 1.00354 | 0.00508 | 0.00448 | 0.00134 | 0.00248 | 0.00120 |
| USSR | 0.00062 | 0.00006 | 0.00077 | 0.00265 | 0.00146 | 0.00153 | 1.00049 | 0.00070 | 0.00004 | 0.00048 | 0.00070 |
| Japan | 0.05810 | 0.00467 | 0.00530 | 0.00754 | 0.00316 | 0.00192 | 0.00262 | 1.00290 | 0.00375 | 0.01036 | 0.00167 |
| Singapore | 0.32053 | 0.01641 | 0.04929 | 0.04926 | 0.03205 | 0.02296 | 0.01801 | 0.16264 | 1.02459 | 0.02364 | 0.03258 |
| China | 0.01147 | 0.00110 | 0.00194 | 0.00351 | 0.00153 | 0.00147 | 0.00365 | 0.02080 | 0.00687 | 1.00044 | 0.00065 |
| India | 0.00879 | 0.00073 | 0.00256 | 0.00266 | 0.00135 | 0.00117 | 0.00840 | 0.00515 | 0.00062 | 0.00022 | 1.00011 |
| Average total indirect impact | 0.0532 | 0.0043 | 0.0219 | 0.0283 | 0.0210 | 0.0139 | 0.0090 | 0.0180 | 0.0033 | 0.0030 | 0.0029 |

$\gamma_{ii}$), and since the initial impact on the net benefits of country $i$ of a change in country $i$'s behavior is always 1, the indirect impact from other countries is the value in the column minus 1. For example, the indirect impact of the United States on itself is 0.00514, and that of Canada on itself is 0.00292. This means that an increase in U.S. GNP will indirectly lead to the United States's net benefits increasing by 1.76 (=0.00514/0.00292) times the net benefits that a similar increase in GNP in Canada would indirectly have on Canada's net benefits.[13]

The second impact that the network formulation allows us to determine, this time from the off-diagonal elements of $(I - \alpha P_1)^{-1}$, is the cross-country indirect impact, $\gamma_{ij}$. This is the impact that country $j$ has on country $i$. The off-diagonal elements for the subsample described above are given in table 6. For example, $\gamma_{12}$ measures Canada's influence on the United States's net benefits, and $\gamma_{21}$ vice versa. In this case, the power of the United States over Canada is about 16 (=0.20949/0.01300) times greater than the power of Canada over the United States. Thus, to determine the effect on any country's net benefits from a change in an independent variable of a different country, $\partial NB_i/\partial x_{mj}$, we compute $\beta_m\gamma_{ij}$. A unit increase in Canada's GNP would lead to the net benefits of the United States increasing by 0.00012 (=0.0092 × 0.01300), whereas a unit increase in the United States's GNP would lead to Canada's net benefits increasing 0.00193. Note that the degree of openness has a substantial effect on $\gamma_{ij}$, as evidenced by the substantially larger values of this quantity for the most open economy in our data set, Singapore.

We can compare the estimated indirect power one country has over another with the average total indirect impact that a country has over *all* other countries combined, to better understand the relationships between countries. The average total indirect impact across all 88 other countries for the subsample we have been following is given in the last row of table 6. Looking just at the average effects, we see that the United States dwarfs all other countries and that the G7 countries generally have the largest. This conforms with conventional expectations and is a helpful check of the procedure used here. We can then compare the average impact with the individual impacts. For the United States, we see in our subsample that it has a greater than average impact only on Canada, Japan, and Singapore. For the United Kingdom, we find a greater than average power relationship with France and Singapore, and for France we find a greater than average power relationship with the United Kingdom, Germany, Italy, and Singapore.

## V. Conclusion

In this paper we augment the conventional probit model to allow for the interdependence across observations that occurs when network externalities are explicitly modeled. We focus on the international ratification of the Montreal Protocol, where the ratification choices of individual nations are correlated for reasons that are both observable and unobservable. Observable factors include income level, form of government, and similar variables that determine the costs and/or benefits of ratification.

Missing from this list is allowance for any network externalities, here formalized as power and public-good effects. With respect to power, if one nation feels strongly about the need to ratify a particular treaty, it will not only ratify the treaty itself but will also try to influence other nations to ratify the treaty as well. We have modeled this unobservable power effect by means of international trade flows: the more country A exports to country B, the more country A would be hurt if country B put trade barriers in the way. Thus, the more reluctant country A will be to pursue a course of action (such as not ratifying) that country B finds undesirable.

When we estimate the magnitude of this power effect, it proves to be statistically insignificant. This outcome holds up in the face of a variety of sensitivity checks. This

[13] Note that the own total effect on the net benefits of country $i$ from a change in the $m^{\text{th}}$ independent variable, $\partial NB_i/\partial x_{mi}$, can be computed for any country $i$ by multiplying the $m^{\text{th}}$ coefficient from the network probit by $1 + \gamma_{ii}$; that is, it is $\beta_m(1 + \gamma_{ii})$. For example, with the $i^{\text{th}}$ country being the United States and the $m^{\text{th}}$ independent variable GNP, the own total effect for the United States would be about 0.00925 (=1.00514 × 0.0092).

nonresult is important nonetheless. Conceptually, power relations based on economic considerations may well play a significant role in international relations, but there is no prior research that has tested for a power effect. In the case of ratification of the Montreal Protocol we find that it does not appear to exist, at least to the degree that it might play out through international trade. One might argue that the international trade conditions of the late 1980s, with the then-existing GATT rules and the ongoing Uruguay Round of negotiations that have since led to the WTO and its dispute resolution procedure, did not allow nations to exercise their power over other nations by threatening international trade flows. This suggests that other power structures might be explored in the future. However, the empirical issues of how to estimate a model incorporating a power effect and how to analyze its implications are no different from what we have explored in this paper.

Despite the public-good properties of ozone-layer protection, we found no evidence that free riding influenced the ratification choice. This suggests why the Montreal Protocol has been such a successful international environmental accord: the incentives for free riding were reduced both by the language in the document and by the private benefits that most nations anticipate receiving from ozone-layer protection.

We have also found that countries with greater civil and political freedoms are more likely to ratify the Protocol and seek emission reductions. This suggests another kind of power relation among nations: the promotion of democratic reforms around the world assists in the ratification of the Montreal Protocol. Moreover, via the power effect the promotion of democratic attitudes influences the behavior of both free and nonfree countries.

Our investigations have broader applications. Theory often suggests interdependent behavior, yet the applied econometric literature has generally been limited in its ability to model interdependent binary decisions due to the difficulties involved in evaluating higher-order multivariate integrals. The RIS method used here is a practical approach to estimating this type of model. Of interest, however, beyond simply the ability to estimate an interdependent probit model is the ability to provide a testable structure for the interdependence. The most common approach to modeling interdependence—and this is true whether the data are continuous, limited, or binary—is to estimate a parameter that assists in identifying a correlation structure. The most familiar and simplest correlation structure is the AR(1) structure used in time series analysis, utilizing a parameter usually called $\rho$. In cross-section applications, the correlation structure is not as easily specified, but can be much more general and will always involve one or a few estimable parameters.

With a more general correlation structure as used in this paper, there are often theoretical constraints that can be imposed and tested. An example from public-sector economics is the issue of how near or adjoining jurisdictions set tax and expenditure policies. It is well known that cities, states, and countries use the fiscal tools available to them to compete with other jurisdictions. Should a given jurisdiction introduce a particular type of tax or offer a particular type of public good? The interjurisdictional power relationship might be based, in part, on the relative rates of existing taxes, relative property values, geographical distance, or some other interjurisdictional connection, and then modeled as described in this paper.

The industrial-organization literature provides the classic example of how to model oligopolies. One approach that is suggested by the current research is to incorporate at least part of the reaction function between firms as a network externality. The decision by airlines to begin, or participate in, a fare war might be shaped by the relative market shares of the relevant carriers in a market, and this could be captured in a power matrix of the form described above.

Labor supply decisions in households with two or more working-age members are likely interdependent: the decision by any of them to enter the labor force depends on the choice of the others. The power matrix might incorporate information about the biological relationship and age difference of household member pairs. These examples, as well as those listed in the introduction, are merely suggestive of the extent and scope of this approach for handling the common problem of interdependent binary decisions.

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## APPENDIX

### Evaluating *n*-Dimensional Probabilities with the RIS Simulator

This appendix describes how to evaluate the $n$-dimensional normal probability given in equation (A2) below. Let $A$ be an upper triangular matrix such that $A'A = (\Theta\Omega\Theta)^{-1}$, and let $\eta = A\epsilon^{**}$. Then $\eta$ is i.i.d. standard normal. Define $B = A^{-1}$; $B$ is an upper triangular matrix with $b_{jj} > 0$ for all $j$. The bounds of the inequality $B\eta = \epsilon^{**} < Z$ can be written as

$$\eta_n < b_{nn}^{-1} Z_n \equiv \eta_{n0},$$

$$\eta_j < b_{jj}^{-1}\left(Z_j - \sum_{i=j+1}^{n} b_{ji}\eta_i\right) \equiv \eta_{j0}(Z_j, \eta_{j+1}, \ldots, \eta_n) \equiv \eta_{j0}. \tag{A1}$$

Let $g(\eta_j)$ be a suitably chosen density function that allows $-\infty < \eta_j < \infty$, and let $G$ be the associated cdf. Define $g^c(\eta_j) = g(\eta_j)/G(\eta_{j0})$ for $\eta_j \leq \eta_{j0}$. Then

$$\begin{aligned} P &= \int_{-\infty}^{Z} \phi_n(\epsilon^{**}; 0, \Theta\Omega\Theta)\, d\epsilon^{**} \\ &= \int_{-\infty}^{\eta_{n0}} \cdots \int_{-\infty}^{\eta_{1,0}} \prod_{j=1}^{n} \phi_1(\eta_j)\, d\eta_1 \cdots d\eta_n \\ &= \int_{-\infty}^{\eta_{n0}} \frac{\phi(\eta_n)}{g^c(\eta_n)} \left[ \int_{-\infty}^{\eta_{n-1,0}} \frac{\phi_1(\eta_{n-1})}{g^c(\eta_{n-1})} \cdots \right. \\ &\quad \times \left. \left( \int_{-\infty}^{\eta_{2,0}} \frac{\phi_1(\eta_2)}{g^c(\eta_2)} \Phi(\eta_{10}) g^c(\eta_2)\, d\eta_2 \right) \cdots \right] g^c(\eta_n)\, d\eta_n. \end{aligned} \tag{A2}$$

The RIS simulator consists of drawing $R$ random vectors of $\eta$ (excepting $\eta_1$) satisfying equation (A-2) from the distribution defined by $g$. Thus, for $r = 1, \ldots, R$, given $\eta_{n0}$, draw $\tilde{\eta}_{n,r}$; determine $\tilde{\eta}_{n-1,0,r}$ from equation (A-2) by using $\tilde{\eta}_{n,r}$ in the place of $\eta_n$; given $\tilde{\eta}_{n-1,0,r}$, drawn $\tilde{\eta}_{n-1,r}$; $\ldots$; given $\tilde{\eta}_{2,0,r}$, draw $\tilde{\eta}_{2,r}$; and determine $\tilde{\eta}_{1,0,r}$ from equation (A-2). Then the simulated value for $p$ is

$$\hat{p} = \frac{1}{R} \sum_{r=1}^{R} \left( \Phi[\tilde{\eta}_{1,0,r}] \prod_{j=2}^{n} \frac{\phi(\tilde{\eta}_{k,r})}{g^c(\tilde{\eta}_{k,r})} \right) \tag{A3}$$

Suitable density functions that can be used for $g$ are the logit, the normal, the $t$, and a transform of the Beta(2, 2) (Vijverberg, 1997). Generating random variables is done fastest when the logit distribution is used, and relatively slow when the normal or $t$ distribution is used. However, one should be more interested in the variability of $\hat{p}$. Although it certainly is not a given that the normal density generates the lowest variability, a test on the basis of the third model displayed in table 4 did suggest that the RIS-normal simulator is preferred.[14] We used $R = 1000$ draws and incorporated a simple antithetical sampling strategy (Vijverberg, 1997). Simulating $\hat{p}$ 100 times, rather than just once as one does when estimating the model, yielded an average log likelihood of $-44.89378$ with a standard deviation of 0.0387, and the RIS-beta generated a value of 0.0411. It is worth noting that the RIS simulator is precise enough, in this case, that the derived (and therefore simulated) values of likelihood ratio test statistics can be relied upon for purposes of testing.

[14] The RIS-normal simulator is identical to what is sometimes called the GHK simulator, which is described in, among others, Börsch-Supan and Hajivassiliou (1993), Hajivassiliou (1993), and Keane (1993).

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