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# Estimating Free-Riding Behavior: The StratAM Model

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Spatial statistical methods in political science provide a tool to deal with spatial and other forms of interdependence in observational data. In this article, I derive a statistical model from a game of impure public goods provision. The resulting strategic autoregressive model (StratAM) allows the researcher to systematically explore the sources of free-riding behavior in the provision of public goods. The StratAM model is tightly related to the well-known spatial autoregressive (SAR) model and can be estimated in a maximum likelihood framework. I demonstrate the use of the StratAM model by analyzing free riding in the provision of foreign aid. Indicators of developmental needs and good governance strongly increase free-riding during the 1990s. Free-riding patterns in the 2000s are more similar to Cold War patterns.

## 1 Introduction

Spatial statistical methods are increasingly used in political science. This is a welcome trend since it is well known that ignoring spatial interconnections can give rise to severe simultaneity biases (Franzese and Hays 2007). At the same time, political scientists cannot rely on geographic proximity to adequately model patterns of interconnectedness (Beck, Gleditsch, and Beardsley 2006). Strong theoretical foundations are essential when using spatial methods, especially since results are very sensitive to specification choices (Plümper and Neumayer 2010).

In this paper, I present an approach to modeling interconnectivity that takes these calls for theoretical guidance seriously. The strategic autoregressive model (StratAM) is derived from a well-known game-theoretic model of impure public goods provision. It incorporates specification choices with explicit grounding in theory.

The StratAM model puts strategic interactions at the center of the empirical analysis. It allows the researcher to both detect free riding in the provision of public goods and systematically test which variables account for the strength of free riding. The model therefore has potentially important applications in the empirical study of public goods phenomena in a wide area of political realms. These range from the international arena, for example, when studying compliance with environmental treaties or contributions to military alliances, to the local level, for example, when analyzing patterns of intercommunal cooperation in road planning or other land use regulations.

The StratAM model is closely related to the well-known spatial autoregressive (SAR) Model (Anselin 1988) and can be estimated in a similar maximum likelihood framework. Both are spatial lag models. Whereas the SAR model incorporates spatial lags into an ordinary least squares (OLS) setup, the StratAM model takes the theory of impure public goods provision as its starting point. The result is a spatial lag model that is nonlinear in parameters.

Analyst face different challenges when employing the two models. In the SAR model, connectivity weights capture the degree to which observations are connected through space. The analyst therefore needs a good understanding of the nature of this spatial connection. In the StratAM model, connectivity weights

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are derived from the theoretical setup and capture the degree of "impurity" of the public good provided. In an applied example that I present below, impurity weights represent the degree to which foreign aid goes toward the creation of a public good, for example, alleviating human suffering, as opposed to generating private consumption value for the donor, for example, generating business for companies in the donor country.

In the first part of this article, I present the derivation of the StratAM model from a game of impure public goods provision. Next, I discuss regularity conditions under which the maximum likelihood estimator (MLE) exists. I then give an example of how the StratAM model can be applied. Looking at foreign aid allocation decisions, I find that free-riding between donors increases in the 1990s for aid given to the poorest countries and those with the best governance indicators. During the 2000s, strategic interactions between donors more closely resemble the Cold War situation.

## 2 Literature

The case for incorporating interconnectivity between observational units into statistical analysis is relatively new. Early forerunners include Beck and Katz (1995), who show that ignoring the simultaneity of concurrent events in panel data is a serious threat to inference. The proposed fix, panel-corrected standard errors, essentially treats interconnectedness as nuisance and does not allow for patterns of interconnectedness that are more theoretically informed.

Fuller attention to the potential of interconnectivity arose when a number of scholars began to pay attention to methodological developments in the statistical study of geography. Naturally, geographers had focused on issues of spatial interconnectivity for a long time. The landmark work on space in econometric analysis is Anselin (1988), who develops a variety of canonical models, including the SAR setup. Franzese and Hays (2007, 2008) have demonstrated how ignoring spatial interconnections biases results and have argued for the universal presence of interconnectedness in phenomena of interest to political scientists. Numerous efforts are underway to incorporate spatial interconnectedness to other frequently used modeling setups, such as event history analysis (Darmofal 2009), dyadic data (Neumayer and Plümper 2010), and limited dependent variable models (LeSage 2000; LeSage and Pace 2009).

Though a growing number of works use the new methodological apparatus, by necessity political scientists cannot rely on geographic space when analyzing interconnectedness (Beck, Gleditsch, and Beardsley 2006). As a possible answer, Murdoch, Sandler, and Sargent (1997) and Franzese and Hays (2008) suggest to think of regression equations with interconnected elements as reduced-form reaction functions of a simultaneous move game. In addition, Plümper and Neumayer (2010) warn that spatial models are very sensitive to specification choices and call for more careful theoretical guidance.

The StratAM model offers solutions to both issues. First, the model takes the suggestion to think of interconnectedness as reaction functions literally. It starts with a game-theoretic model. In this model, interconnectedness arises naturally from the strategic interactions between actors. Second, since the StratAM model preserves this game-theoretic structure, specification choices are carefully guided by theory.

## 3 A Formal and Statistical Model of Impure Public Goods Provision

For illustration purposes, throughout the discussion of the formal model I will use the example of the provision of foreign aid. The notion that donor countries see development as a public good was first proposed by Olson and Zeckhauser (1966). Economic growth, social indicators, and other developmental concerns are nonexcludable and nonrivalrous in how donors enjoy them, meeting the classic definition of a public good. At the same time, it is widely recognized that donors also use aid to gain private advantages such as securing diplomatic influence or giving support to their export industries. Whereas existing empirical approaches typically ignore this distinction, my model captures both of these motives.

My exposition of the public goods game is based on a textbook example (Varian 1992, 420). I expand the textbook model to accommodate the impurity of the public good. The model represents a single-shot simultaneous move game with complete information. The players are $N$ international aid donors, each denoted $i = 1, \ldots, n$. A donors's utility is given by

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$$U_i = \lambda f\left(b_i a_i + \sum_{j \neq i} b_j a_j\right) + f(m_i - b_i a_i), \tag{1}$$

where $a_i$ is the aid provided by player $i$ and $m_i$ is her endowment. The function $f(x)$ that maps consumption into utility levels is strictly increasing and concave, that is, $f'(x) > 0$ and $f''(x) \leqslant 0$, $\forall x$. It is assumed to have identical functional form for both public and private goods. However, the parameter $\lambda \geqslant 0$ scales how much utility player $i$ derives from private versus public goods consumption and thus allows for sufficient flexibility. At this stage, the precise functional form of $f(x)$ is not relevant. However, to ensure existence of a closed-form equilibrium solution, we will impose more structure below.

The weights $b_i \in [0, 1]$ capture the extent to which individual payments contribute to the public good. In the context of aid provisions, tying aid to specific projects or imports from one donor country constitutes private consumption for the donor and reduces the public good input enjoyed by all players.

The donor needs to compare the utility of providing aid against how much to spend on private consumption. Her benefit from aid provision in turn is a function of the weighted sum of her own and all other aid contributions, $b_i a_i + \sum_{j \neq i} b_j a_j$. The donor directly consumes what is left over from the endowment after giving aid plus the private good component of aid, $m_i - a_i + (1 - b_1)a_i = m_i - b_1 a_i$.

In equilibrium, each donor chooses an aid level $a_i^*$ that maximizes equation (1), subject to budget and nonnegativity constraints that can be summarized as $0 \leqslant a_i^* \leqslant m_i$. Assuming an interior solution, the first-order condition to this problem is, for all $i$,

$$\frac{\lambda f'\left(b_i a_i + \sum_{j \neq i} b_j a_j\right)}{f'(m_i - b_i a_i)} = 1. \tag{2}$$

This first-order condition has a well-known economic interpretation. The left-hand side represents $i$'s marginal rate of substitution between public goods and private goods consumption, whereas the right-hand side is $i$'s marginal cost of providing the public good.

Solving equation (2) for $a_i$ gives the best response function $a_i^*(a_{-i})$. This step requires fixing a functional form $f(x)$ that satisfies the constraints given above. A simple utility function that does so is $f(x) = ln(x + 1)$, with $f' = 1/(x + 1)$. This choice is somewhat arbitrary, and other possible functional forms come to mind. Below, I show the results of a Monte Carlo analysis, where I evaluate how choosing another functional form affects the performance of the model. It turns out that misspecification of $f(x)$ leads to mild bias, but the StratAM model still widely outperforms a simple SAR specification in a public goods context.[1] Substituting into equation (2), we can now solve for $a_i$:

$$\lambda \frac{1}{b_i a_i + \sum_{j \neq i} b_j a_j + 1} = \frac{1}{m_i - b_i a_i + 1}, \tag{3}$$

$$a_i = -\frac{1}{\lambda + 1} \sum_{j \neq i} \frac{b_j}{b_i} a_j + \frac{\lambda}{\lambda + 1} \frac{m_i}{b_i} + \frac{\lambda - 1}{b_i(\lambda + 1)}. \tag{4}$$

To reduce clutter and facilitate comparison with the SAR model down the road, I reparameterize $\rho = \frac{1}{\lambda+1}$, $\rho \in (0, 1]$. This gives us the best response function

$$a_i^*(a_{-i}) = -\rho \sum_{j \neq i} \frac{b_j}{b_i} a_j + (1 - \rho)\frac{m_i}{b_i} + \frac{1 - 2\rho}{b_i}. \tag{5}$$

We thus see that player $i$'s equilibrium spending $a_i^*$ decreases with aid $a_j$ given by other players $j$. This is the typical free-riding result in public good situations. The negative influence of other actor's contributions is weighted by a ratio of the respective public good weight $b_j$ and $i$'s own weight $b_i$ and, crucially, parameter $\rho$, which is a function of $i$'s appetite for public goods consumption relative to private

[1] It would also be possible to allow for some degree of endogeneity in choosing $f(x)$, for example, by using Cobb-Douglas utilities with $f(x) = x^\alpha$, $\alpha \in [0, 1]$. Estimation of $\alpha$ is possible but requires numerical solving of the likelihood function at each reiteration of the MLE optimization procedure. Since this adds considerable computational difficulty, here we choose a simpler approach.

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goods consumption. If $i$ values public goods consumption more highly, $\lambda$ increases, resulting in a lower $\rho$ and less free riding. Substantively, this is because higher valuations of the public good induce actor $i$ to internalize more of the social costs of free riding.

The optimal public goods provision $a_i^*$ also increases with $i$'s endowment $m_i$, representing an intuitively appealing endowment effect. This effect is weighted by $i$'s public good weight $b_i$, with an increasing effect as the share of money that really goes toward the public good (i.e., $b_i$) declines. As was the case with free riding, the endowment effect grows larger as $i$'s relative taste for public goods consumption increases.

The last term adjusts the overall level of equilibrium spending. Its precise form is mainly an artifact of the functional form assumption about utilities $f(x)$. It too is a function of $i$'s relative taste for public goods, with bounds $-1/b_i$ and $1/b$. Thus, the term adds to the level of public goods provision if $i$ more heavily values public versus private goods consumption ($\lambda > 1$, implying $\rho < .5$). But it lowers provision levels in the opposite scenario.

Overall, actor $i$'s relative taste for public goods consumption affects her decision how much to contribute through three channels; first by reducing her inclination to free ride on the contributions of others, second through the endowment effect, and third directly through the relative taste for public versus private goods consumption. Since we are interested in developing an estimator for free-riding behavior, we need to keep these three distinct channels in mind later in the analysis.

The equilibrium of the game is found by solving the system of $n$ best response functions defined by equation (5). The system of equations can be conveniently summarized in matrix notation as

$$\mathbf{A} = -\rho\mathbf{W}\mathbf{A} + (1-\rho)\mathbf{M} + (1-2\rho)\mathbf{L}, \tag{6}$$

where $\mathbf{A}$ is an $n \times 1$ column vector of optimal responses $a_1^*, \ldots, a_n^*$, $\rho$ and $1-\rho$ are scalars as defined above, and $\mathbf{M}$ and $\mathbf{L}$ are $n \times 1$ column vectors. $\mathbf{M}$ contains weighted endowments $m_1/b_1, \ldots, m_n/b_n$, and $\mathbf{L}$ contains elements $1/b_1, \ldots, 1/b_n$. $\mathbf{W}$ is an $n \times n$ weight matrix of the form

$$\boldsymbol{W} = \begin{bmatrix} 0 & \frac{b_2}{b_1} & \cdots & \frac{b_n}{b_1} \\ \frac{b_1}{b_2} & 0 & \cdots & \frac{b_n}{b_2} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{b_1}{b_n} & \frac{b_2}{b_n} & \cdots & 0 \end{bmatrix}. \tag{7}$$

To reemphasize, the off-diagonal elements of $\boldsymbol{W}$ are formed by the ratio of public good weights $b_j/b_i$, which is directly derived from the best response function (5).

Actor $i$ is willing to free ride more on $j$'s provision of the public good if $b_j/b_i$ is large. That is, $i$'s free-riding behavior is stronger if $j$ is able to contribute to the public good with less impurity than $i$. In the boundary case of $b_i \to 0$ (assuming $b_j > 0$ and $\rho > 0$), this will drive $i$'s contribution levels to 0. It is worthy to note that there is nothing unusual about the special case of pure public goods provision. In this case, all ratios $b_j/b_i$ are equal to 1, but this also obtains if there is symmetry in impurities between actors for any value of $b_{i,j}$ (with the exception of $b_{i,j} = 0$, in which case no actor has the ability to provide anything to the public good).

To ensure the game has a unique equilibrium, we need to consider uniqueness of the solution to the system of equations (6). Fortunately, the system is linear in $a_i$ with coefficient matrix $\mathbf{I} + \rho\mathbf{W}$, where $\mathbf{I}$ is the $n \times n$ identity matrix. Thus, there exists a unique solution if and only if $\mathbf{I} + \rho\mathbf{W}$ has full rank. We will revisit this result in the discussion of the statistical properties of the StratAM model below.

A necessary step in structural estimation of games is the inclusion of a stochastic component (Signorino 1999; Carrubba, Yuen, and Zorn 2007). The literature identifies three principal sources of uncertainty: incompleteness of the information that players have about payoffs of other players, erroneous decisions on parts of players (agent error), and measurement error on part of the analyst (regressor error) (Signorino 2003).

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For purposes of deriving the StratAM model from equation (6), agent and regressor errors are equivalent.[2] Both result in a statistical model of the form

$$\mathbf{Y} = -\rho\mathbf{W}\mathbf{Y} + (1-\rho)\mathbf{M} + (1-2\rho)\mathbf{L} + \mathbf{e}. \tag{8}$$

The model now features the disturbance term $\mathbf{e}$, an $n \times 1$ column vector of i.i.d. normal stochastic disturbances $\varepsilon_i$ with common variance $\sigma^2$ and mean $\mu = 0$.[3] The endowment term $\boldsymbol{M}$ now contains actual data. In the foreign aid example, this could be the overall budget of each donor government.[4] The vector of dependent variables is named $\mathbf{Y} = \mathbf{A}$, following convention.

What is the substantive interpretation of the estimate for $\rho$? Conceptually, the model in equation (8) is closely related to the SAR model, $\boldsymbol{Y} = \rho\boldsymbol{W}\boldsymbol{Y} + \boldsymbol{X}\beta + \mathbf{e}$. The similarity stems from the endogenous part $\rho\boldsymbol{W}\boldsymbol{Y}$ (which only differs in the sign of $\rho$).[5] The interpretation of $\rho$ in the SAR model is as the strength of the spatial association between observations. In the StratAM setup, space is replaced through strategic interconnectedness. The parameter $\rho$ still captures free-riding behavior but also influences $\boldsymbol{Y}$ through the endowment and relative utility weight effects.

Presenting the StratAM model in the form given in equation (8) was useful to establish its conceptual closeness to the SAR setup and to develop intuition about the interpretation about parameter $\rho$. The parameter $\rho$ is at the center of the researcher's interest. It provides us with a natural measure of the intensity of free-riding behavior. The parameter could be directly estimated, but we would like to be able to test theories under which circumstances free-riding increases or decreases. In a last step, we therefore make a final change to the StratAM setup to accommodate covariates. Going back to the original definition of $\rho$, we write

$$\rho = \frac{1}{1+\lambda} = \frac{1}{1+\exp(\boldsymbol{Z}\gamma)}, \tag{9}$$

where the original utility weight $\lambda$ is replaced by a linear additive term consisting of variables $\boldsymbol{Z}$ and coefficients $\gamma$. The exponential transformation of $\boldsymbol{Z}\gamma$ ensures that this term maps into the bounds of $\lambda$, that is, $[0, \infty)$.

The StratAM analysis produces various quantities of interest. The immediate output of the MLE procedure is coefficient estimates for the linear additive term $\boldsymbol{Z}\gamma$. Equation (9) shows that parameter $\rho$ decreases as $\boldsymbol{Z}\gamma$ gets larger. Thus, positive estimates of $\gamma$ imply that larger values of the variables $\boldsymbol{Z}$ decrease free riding. However, in order to quantify this effect we must recognize that $\rho$ influences public goods provision levels $\boldsymbol{Y}$ also through the endowment and relative utility weight effects. The absolute size of the free-riding effect also depends on the values of the weights $b_j/b_i$ and the provisions levels by other players $j \neq i$.

To recover marginal effects of the covariates on free riding, we therefore have to pay attention to the actors' individual endowment levels and impurity weights in a counterfactual exercise. To this end, we need to fix endowments $m_i$ and impurity weights $b_i$. We then choose a representative profile of regressors $\boldsymbol{Z}\gamma$. Typically, we would vary one of the variables, say $Z_k$, over its entire observed range while keeping the other variables at representative values, for example, their respective medians. Next, we generate a set of predicted values $\hat{\boldsymbol{Y}}$ for each counterfactual value of $Z_k$.[6] At each point for $Z_k$, this set of predicted values consists of $n$ predictions, one for each actor.

[2] This is because players only move once. Since they also move simultaneously, the players do not have more information than the analyst.

[3] The only way to incorporate incomplete information is adding uncertainty about the size of endowments $m_i$. This would make player $i$'s best response a function of $n-1$ errors $\varepsilon_j$, $j \neq i$.

[4] In earlier versions of this paper, I reparameterized $M$ with covariates $\mathbf{X}\boldsymbol{\beta}$ to allow researchers to include variables that affect overall levels of aid. This led to severe numerical problems when simultaneously estimating the parameters $\beta$ and the $\gamma$ from the second set of covariates $\boldsymbol{\gamma}$ introduced below. In the interest of concentrating on the sources of free-riding behavior, I decided to focus on this latter set of covariates.

[5] An additional similarity arises when replacing $\boldsymbol{M}$ with covariates $\boldsymbol{X}\beta$.

[6] Predicted values are obtained as solution to the following system of equations:

$$\hat{\boldsymbol{Y}} = (\boldsymbol{I} - \rho\boldsymbol{W})^{-1}(1-\rho)\boldsymbol{M} + (\boldsymbol{I} - \rho\boldsymbol{W})^{-1}(1-2\rho)\boldsymbol{L}.$$

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Since the predictions $\hat{\boldsymbol{Y}}$ account for all three pathways through which $\rho$ exerts an influence, we need to take a second step. To make a statement about free riding, we would like to compare a players's allocation to the public good to a hypothetical allocation she would be making if the good was private instead. To find the right counterfactual, I go back to the utility function (1) and set other players' contributions to the public good to zero, $a_j = 0$. Solving for all players' best responses and reparameterizing as before, the resulting structure is equivalent to the StratAM model without the free-riding term, $\boldsymbol{Y} = (1-\rho)\boldsymbol{M} + (1-2\rho)\boldsymbol{L}$. Using this functional form and estimates and regressors $\boldsymbol{Z}\gamma$ from before, we can create a second set of predicted values, $\hat{\boldsymbol{Y}}'$.[7]

Finally, we subtract $\hat{\boldsymbol{Y}}' - \hat{\boldsymbol{Y}}$ to obtain $\hat{\boldsymbol{Y}^F}$. This quantity captures the predicted loss due to free riding. Finally, we calculate predicted marginal effects of $Z_k$ by taking first differences of the individual elements of $\hat{\boldsymbol{Y}}^F$.[8] We can use a parametric bootstrap method to simulate confidence bands around these effect estimates (e.g., King, Tomz, and Wittenberg 2000).

Before turning to the statistical properties of the StratAM model, a brief discussion of data structure is in order. In applied settings, social scientists typically deal with cross-sectional time-series data. Since the StratAM model is based on a single shot game, how does the model handle time? In principal, it is easy to rewrite equation (8) to accommodate time.[9] However, this does not address the issue of temporal dynamics. From an econometric perspective, we could try to model these by including temporal lags into the specification (Franzese and Hays 2008). But such a move would have no basis in theory. Since the advantage of the StratAM approach lies in preserving the theoretical structure of the model, we need to look to theory for solutions.

From a theoretical perspective, repeated interactions between strategic players give rise to folk theorem–type situations with multiple equilibria. One possibility to deal with this is to restrict the analysis to Markov stratgies (Fudenberg and Tirole 1991), but the methodological challenges in deriving a structural estimator from the resulting stochastic dynamic game are formidable. Instead, I propose that the StratAM model can be applied in dynamic settings if we are willing to treat data points as repeated independent realizations of the stage game. If actors are engaged in long-term relationships in an information-rich environment and if they have incentives to 'play it right', for example, because of relative scarcity of resources or institutional imperatives, their policies will be stable over time. In this environment, we can think of the stage game as the limiting equilibrium of a long-running repeated game.

Although this probably still does not justify the use of annual data, substantive considerations can guide the decision to use averages over longer time periods. A starting point might be existing examples such as provided by the empirical growth literature, where 4- or 5-year averages are commonly used to deal with issues of short-term volatility and autocorrelation.[10]

## 4 Properties of the Model

The close conceptual relationship between the StratAM and SAR models means that we can rely on the canonical work by Anselin (1988) to establish the regularity conditions for the MLE estimator of the StratAM model. The log-likelihood function will be well behaved if the structure of strategic interactions, expressed by $\rho$ and the weight matrix $\boldsymbol{W}$, does not lead to explosive behavior. As discussed above, the stage game has a unique solution if the coefficient matrix $\boldsymbol{I} + \rho\boldsymbol{W}$ has full rank. It turns out that this matrix also plays an important role from an econometric perspective.

[7] Estimating $\boldsymbol{Y} = (1-\rho)\boldsymbol{M} + (1-2\rho)\boldsymbol{L} + \boldsymbol{e}$ separately would lead to biased results because of functional form misspecification.

[8] Note that it might be necessary to adjust for step size if the values of $Z_k$ do not reflect unit increases.

[9] Following notational convention for time-space recursive models (Anselin, Le Gallo, and Jayet 2008), we can write

$$\mathbf{Y} = -\rho(\mathbf{I}_T \otimes \mathbf{W}_N)\mathbf{Y} + (1-\rho)\mathbf{M} + (1-2\rho)\mathbf{L} + \mathbf{e},$$

where $\mathbf{I}_T \otimes \mathbf{W}_N$ is a block diagonal weight matrix with $N \times T$ cross-sectional weight matrices $\boldsymbol{W}$ on its diagonal.

[10] From an econometric perspective, recent advances in spatial statistics allow for the incorporation of dynamic elements, for example, in the form of serial correlation of error terms (Anselin, Le Gallo, and Jayet 2008), or temporal-spatial lags of the left-hand side variable (Giacomini and Granger 2004). However, these approaches do not easily map to repeated choice behavior in a strategic environment.

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The StratAM model from equation (8) can be rewritten as

$$\boldsymbol{Y} = (\boldsymbol{I} + \rho \boldsymbol{W})^{-1}(1-\rho)\boldsymbol{M} + (\boldsymbol{I} + \rho \boldsymbol{W})^{-1}(1-2\rho)\boldsymbol{L} + (\boldsymbol{I} + \rho \boldsymbol{W})^{-1}\mathbf{e}, \tag{10}$$

where $\boldsymbol{I}$ is the $n \times n$ identity matrix. From the last term, it is clear that the joint distribution of $\boldsymbol{Y}$ needs to be derived from the i.i.d. normal disturbances $\mathbf{e}$ via the structure $\boldsymbol{I} + \rho \boldsymbol{W}$. Using the change-of-variable technique, this transformation involves the Jacobian $|\boldsymbol{I} + \rho \boldsymbol{W}|$. To ensure non-explosive behavior, we must have $|\boldsymbol{I} + \rho \boldsymbol{W}| > 0$ (Anselin 1988, 63). This is essentially the same condition that guarantees full rank of the coefficient matrix $\boldsymbol{I} + \rho \boldsymbol{W}$ and the existence of a unique solution to the system of best response functions of the stage game.

The StratAM model imposes a particular structure on the data. In the spirit of Occam's razor, we should therefore ask whether the costs of imposing this structure are worth the insights we might gain. A potential alternative to the StratAM is the SAR model. As a generalization of OLS, it belongs to the widely used family of linear regression models, and its properties are well established.[11] In addition, some authors have used SAR to analyze free-riding behavior in the provision of a public good (Murdoch, Sandler, and Sargent 1997). There are two key areas of difference between the StratAM and SAR models.

First, in the SAR model, connectivity weights capture spatial connectivity. This is appropriate if spill-in effects from public goods provision are in fact determined geographically. For example, efforts to reduce airborne pollutants also benefit neighboring states (Murdoch, Sandler, and Sargent 1997). The SAR model is a natural candidate for modeling these geographic patterns. The StratAM model can help if no geographic interpretation of interconnectedness exists. In the model, connectivity weights capture the impurity of the public good. In the example of foreign aid, this is the degree to which aid goes toward developmental versus private purposes.

Second, the StratAM model reparameterizes the connectivity parameter $\rho$ with covariates. This allows for flexibility in modeling variation in free-riding behavior. Although the SAR model also can accommodate variation in free-riding behavior, $\rho$ is estimated as a single parameter. Any variation results from the linear additive term $\boldsymbol{X}\beta$ that propagates via the simultaneity component $\rho \boldsymbol{W}\boldsymbol{Y}$ in a non-linear fashion. The effect of an individual variable on free riding therefore depends on the absolute level of the covariates $\boldsymbol{X}\beta$. This effect is bound to be much smaller than in the more flexible StratAM approach. A researcher who seeks to explore systematic variation in free-riding behavior is therefore better served with the StratAM model.

In the following example, I use the StratAM model to analyze the sources of free-riding behavior in the provision of foreign aid. I also compare the results to an SAR analysis, illustrating the differences between the approaches.

## 5 Example

In the following, I apply the StratAM model to the allocation of official development aid (ODA).[12] The question why donors give aid, to whom and how much, has spanned a large empirical literature. Here is not the place to exhaustively review this literature. To my knowledge, none of the existing studies explores and controls for the conditions under which free riding affects aid provision. To demonstrate the use of the StratAM model, I investigate which factors affect the provision of aid by 15 OECD donor countries to 96 recipient countries, for the time periods 1986–1989, 1994–1997, and 2002–2005.

Key specification choices in applying the StratAM model to this problem are the impurity weights $b_i$, actor endowments $m_i$, and the covariates $\boldsymbol{Z}$ used to reparameterize the strategic connectivity parameter $\rho$. I choose the tying status of aid to represent the impurity weights $b_i$. Tied aid requires recipient governments to spend the money with providers of goods and services in the donor country. Examples include no-bidding requirements on public contracts or aid in the form of export credits. Tying status is not a perfect measure because even though it leads to inefficiencies (Jepma 1991), tied aid still can serve to create public goods. Despite this shortcoming, it seems reasonable that higher tying rates are associated with

[11] However, it should be noted that linear specifications can suffer from functional form misspecification if the data-generating process is strategic in nature (Signorino and Yilmaz 2003).

[12] The variable measures net flows of ODA in constant 2006 dollar terms (OECD 2009).

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greater private benefits that accrue to the donor. The variable is calculated using the OECD's Creditor Reporting System (2009) that breaks down aid provisions by tying status. These data are self-reported. Unfortunately, the U.S. stopped reporting tying practices in the early 1990s. I therefore exclude the United States from the analysis from the two later time periods.

As endowments $m_i$ I use total government consumption. This captures the total share of economic activity by the state. I take this variable from the World Bank's World Development Indicators (2009). In order to motivate the choice of covariates $\boldsymbol{Z}$, it is necessary to briefly review some theory and existing work on aid allocations.

Among the most influential recent studies of aid allocation is an article by Alesina and Dollar (2000). Many authors have sought to replicate their findings, in whole or in part, often using additional data, different variables, or other econometric specifications (examples include Alesina and Weder 2002; Berthélemy and Tichit 2004; Berthélemy 2006; Dollar and Levin 2006). The contributions of these later works not withstanding, the original piece identifies important motivations for giving aid. Following Lancaster (2007), we can roughly categorize these motivations into three categories.

The first category is genuine concerns about development. According to this, aid should go to needier countries, that is, those with lower GDP per capita should receive more support. In addition, more aid should be given to countries that have the best prospects of making good use of it in terms of fostering growth. Aid effectiveness has been tied to good government policies and institutions (Knack and Keefer 1995; Burnside and Dollar 2000). Anecdotal evidence suggests that donors reward political stability and growth orientation. An example of this is Botswana (Acemoglu, Johnson, and Robinson 2003).

What are the implications for strategic interactions between donors? Development success has classic public goods characteristics (Olson and Zeckhauser 1966). Donor countries can equally enjoy development success, whether they contributed to it or not. This suggests that development-oriented aid is subject to free riding between donors. Accordingly, we should expect that aid to countries with higher GDP per capita is subject to less free riding as development issues become less pressing. Since better institutions increase aid effectiveness and therefore accentuate the public good properties of aid, we also expect that better institutions are associated with more free riding. The latter is a counterintuitive and provocative hypothesis. It implies that those recipient countries that could make the best use of foreign aid are systematically undersupplied with aid because of collective action problems between donors.

The second category of donor motivations is diplomatic considerations. Foreign aid was historically first used as an instrument of foreign policy (Morgenthau 1962; Lancaster 2007). Strategic interests played an important role not only during the Cold War but also for Western aid to Egypt and Israel. Their continuing relevance after the end of the confrontation between East and West remains an open empirical question. From the perspective of strategic interactions, predictions about free-riding behavior depend on the context of donor interests. Shared interests, such as in the support of stability in the middle east, should lead to greater free riding. But interests can also diverge. France, for example, has used aid to former colonies in Africa as a tool to maintain an active sphere of influence. Since former colonial ties imply a variety of idiosyncratic interests, we should generally expect less free riding in the provision of aid to former colonies. Another measure of bilateral diplomatic influences on aid is voting behavior in the UN General Assembly. The more a recipient country votes alongside a particular donor, the more aid this donor will provide (Oatley and Yackee 2004; Stone 2004; Barro and Lee 2005; Carter and Stone 2010). We therefore should see larger vote shares associated with less free riding.

I include two other variables in the strategic aid category, the shares of Muslims and Catholics in the population. Although cultural affinities might play a role, only Austria, Belgium, France, and Italy are majority Catholic among the 15 OCED donors in the sample. None is majority muslim. For Muslim countries, I expect that Western donors share strategic concerns about regional stability and access to oil. This in turn should translate into increased free riding. The case for the Catholic population variable is less straightforward. It most likely proxies for Latin America. To the extend that the United States plays a predominant role in this region, free riding should be decreased.

Finally, we need to consider how historic events will affect free riding in different time periods. It is a consensus view that Western foreign aid practice substantively changed at the end of the Cold War. Although the confrontation between East and West was ongoing, developmental goals often took a backseat to diplomatic and strategic goals. This changed during the 1990s when Western donors openly embraced

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developmental performance and the promotion of 'good governance' as new policy goals (Schraeder, Hook, and Taylor 1998; Lancaster 2000; Santiso 2001; Dreher 2004; Dunning 2004). However, there is mounting evidence that this trend was reversed in reaction to the attacks of September 11, 2001. Security concerns, specifically the need to deny safe haven to internationally active terrorists, not only have become a new focus of U.S. aid but also have affected other Western aid programs (Boutton and Carter 2010; Fleck and Kilby 2010).

Our exploration of free-riding behavior in the three time periods can help to collaborate this historic narrative. Greater development orientation of aid implies increased collective action problems. We should therefore expect that variables associated with developmental concerns (GPD per capita) and good governance (rule of law, bureaucratic quality, democracy) will increase free riding more during the 1990s than in the Cold War and post-9/11 periods. At the same time, diplomatic variables that tap into shared Western interests (Egypt and Israel dummies) should account for more free riding during these periods. The forecast for bilateral strategic variables (UN vote share, former colony) should be less affected by the resurgence of strategic concerns. Arguably the reforms of the 1990s have discredited the open use of aid to secure bilateral advantages.[13] We therefore should expect these variables to reduce free riding significantly during the Cold War but less so in the later time periods.

The results of the analysis are summarized in Fig. 1.[14] I calculated effect sizes keeping donor government share of GDP as endowments $m_i$ and tying status as connectivity weights $b_i$. Variables of interest were varied from their observed minimum to their maximum value, while keeping others at their medians. For dyadic variables, I did this separately for each donor country. The StratAM model generates a separate marginal effect for each of the 15 donor countries (14 for the two later time periods). I report effects with the smallest magnitudes.[15]

The plots in Fig. 1 show the marginal effect of each variable on losses from free riding per donor and recipient country. Positive numbers indicate more free riding, that is, the marginal reduction in aid provision. Dots represent point estimates, one for each of the three time periods. The bars extending left and right show 95% confidence bands. A dotted vertical line marks the null axis. Confidence bands that cross this line indicate that the effect is not statistically significant at the 5% level.[16]

We begin with the variables that capture strategic interactions in the provision of development-oriented aid. The most important predictor of aid allocations is GDP per capita. We predicted that aid to poorer countries would be more development oriented and thus should be subject to more free riding. This is consistently the case for all time periods. In the late 1980s, a one unit decrease in purchasing power parity (relative to the United States) per capita increased free-riding losses on average by $2.18 million per donor. This effect was slightly greater in the 1990s ($3.09 million) and decreased to $0.597 million in the most recent period. Although we should not make too much of the magnitude of changes between time periods, increased free riding during the 1990s is congruent with a policy shift to developmental goals during this period. With the reemergence of strategic considerations in aid provision in the first decade of the new century, this trend is reversed.

Bureaucratic quality, democracy, and the rule of law do not consistently increase free riding, but the emerging temporal pattern follows the prediction for the different periods. In the 1980s, a better institutional environment actually had a dampening effect on free riding. Bureaucratic quality and democracy are both statistically significant, whereas law and order just misses the 5% level. In sharp contrast, during the 1990s, all three variables contribute substantively to free riding.[17] A one-point improvement on the 0 to 4 bureaucratic quality scale was associated with average free-riding losses of $22.1 million per donor, a sizable drop. On the similar rule-of-law scale, a one-point increase induced a drop of $23.3 million per donor. In the post-9/11 period, this effect reversed back into negative territory for all three indicators, though bureaucratic quality misses statistical significance. Overall, the congruence of the temporal pattern

[13] This can be seen, for example, in the UN drive to eliminate aid tying.

[14] As mentioned in the discussion of the model, the key quantity of interest in the StratAM analysis is marginal effects of the covariates on free-riding behavior. The coefficient estimates $\gamma$ can only give an idea of the direction of this effect but not of its size or statistical significance. For completeness, parameter estimates for all three time periods are reported in Table 1 in the Appendix.

[15] The applied researcher might be interested in investigating the fine structure of the aid allocations. The StratAM model allows her to pay close attention to differences in effect sizes between donor countries.

[16] The graphical presentation was inspired by Kastellec and Leoni (2007).

[17] Democracy is just significant at the 5% level, with a lower bound of 0.038.

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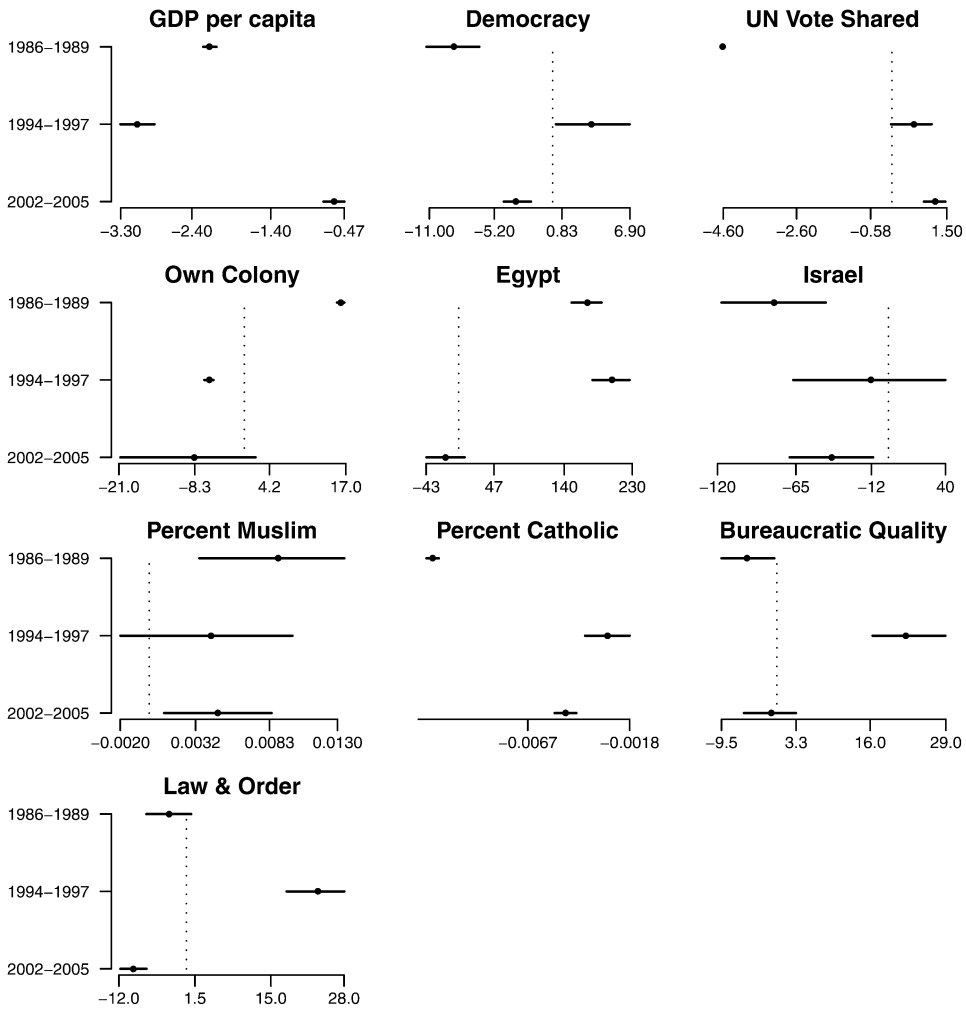



**Fig. 1** Marginal effects of variables on free-riding losses.

for all four variables that capture the development orientation of aid supports the hypothesis that Western aid policies briefly became more development oriented during the 1990s, before shifting back toward strategic interests in the wake of the 9/11 attacks.

We next turn to the variables that capture strategic interests. We argued that aid to Egypt and Israel is driven by shared strategic interests of the major OECD donors in the sample. Accordingly, we should see increased free riding during the Cold War and the post-9/11 periods. This temporal pattern is not born out for Egypt. Aid provision to the country was subject to substantive free riding in the 1980s, but this effect did not decrease during the 1990s. For 2002–2005, aid to Egypt reduced free riding but not in a statistically significant manner. On average, donors in the 1980s where likely to give $171 million less in aid to Egypt because of free riding and $203 million less in the 1990s. The unexpected reduction in free riding after 2000 possibly reflects efforts by the United States to reduce aid to the country as its strategic focus did move to other countries in the region.

The results for Israel display a distinct temporal pattern, but it is the opposite of what we expected. Aid to Israel was substantively less subject to free riding than support for other countries during the Cold War and the post-9/11 period. During the 1990s, this effect vanished. To gauge substantive effect size, in the 1986–1989 period, free riding on average decreased by $80.2 million per donor, and somewhat less in the 2000s. How do we explain this deviation from our expectations? It is possible that donors are better able to overcome free-riding problems when coordinating aid to Israel. However, such a claim awaits a sound theoretical explanation. Perhaps more convincingly, the discovered pattern fits a logic that

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aid to Israel follows strategic considerations that are not subject to public good problems. Candidates are, controversially, domestic pressures in the United States (Mearsheimer and Walt 2006) or the special historic role of Germany in supporting Israel (Feldman 1999).

The variables that measure competitive strategic interests are UN vote share and status as former colony. During the 1980s, UN voting behaves as expected. During this period, a one–percentage point increase in voting in lockstep with a particular donor caused a $4.62 million increase in aid from this donor due to reduced free riding. In the 1990s, UN voting becomes statistically insignificant. For 2002–05, the effect of shared voting swings into positive territory, with each percentage point increase in voting leading to an increase of free-riding losses by $1.18 million. The free-riding effects of UN vote share therefore exactly fit the predicted pattern of bilateral 'vote buying' during the Cold War and less competitive behavior after the 1990s.

The colony variable does not behave as expected during the Cold War. Former colonial powers gave on average $16.2 million less in aid because the special bilateral relationship they enjoyed with former colonies increased free riding. In the 1990s, this effect is reversed, indicating a break with Cold War practices, and a move toward more selective aid. Average reductions in free-riding losses in this period amount to $5.89 million. There is no evidence of a reversal to Cold War practices in the 2000s as the variable loses statistical significance. This observed pattern does not fit the narrative that colonial ties served as strategic assets during the Cold War and was replaced with a more development-oriented policy after 1990. It is possible that the free riding during the 1980s reflects the coherence of strategic interest of Western donor nations during the Cold War. This would contradict our assumption that former colonial status reflects primarily a bilateral relationship. More research into the strategic dynamics of lead donorship across several Western donors is necessary.

Finally, an increasing share of Muslims in the population increases free riding, as expected. This effect is strongest during the Cold War. In line with our expectations, the effect decreases (and loses statistical significance) during the 1990s and reemerges in the post-9/11 period. However, effect sizes are small and we should not make too much of this finding. For example, in the 1980s, a 1% increase in population share only translated into an additional $8,910 in aid lost to free riding per donor. Catholic population shares display similarly negligible substantive effects.

Overall, the observed free-riding patterns confirm that Western aid policies were more strategic during the Cold War and became more development oriented during the 1990s. In the years after the September 11 attacks, these trends partly reversed.

In the following section, I compare the StratAM results to those from an SAR model. To establish a fair basis for comparison, I keep the dependent variable, the weight matrix, and the independent variables the same. I add government consumption as independent variable since this enters the StratAM model as government endowment. Any differences in results should reflect the different functional forms of the models.

Figure 2 shows marginal free-riding effects from the SAR model and the previous StratAM results.[18] A cursory inspection shows that the main difference between the models is absolute effect size. As expected, the SAR model attributes much smaller free-riding effects to individual variables, on the order of one to two magnitudes. Therefore, all effect sizes end up diminished or of no substantive significance.

The direction of effects switches between the StratAM and SAR results. This reversal occurs because the SAR analysis finds complementarities in aggregate aid provision.[19] Thus, any variables associated with higher aid levels also trigger complementary aid allocations. In contrast, the StratAM model splits away the public from the private goods content of aid and concentrates on the former. Thus, variables that increase aid levels will lead to more free riding. This comparison illustrates that the models can produce quite different results in applied analysis. Model choice ultimately depends on the theoretical expectations of the researcher and on the practicalities of specifying connectivity weights. The StratAM model can help in situations of impure public goods provision and when connectivity weights are not determined through geography.

[18]SAR free-riding effects were calculated in the same fashion as before. Free riding is the difference between predicted values from the full model, $\hat{\boldsymbol{Y}} = (\boldsymbol{I} - \rho \boldsymbol{W})\boldsymbol{X}\boldsymbol{\beta}$, and the linear predictions $\hat{\boldsymbol{Y}}' = \boldsymbol{X}\boldsymbol{\beta}$.

[19]The spatial parameter $\rho$ is positive in all three time periods. See estimation results in Table 2 in the Appendix.

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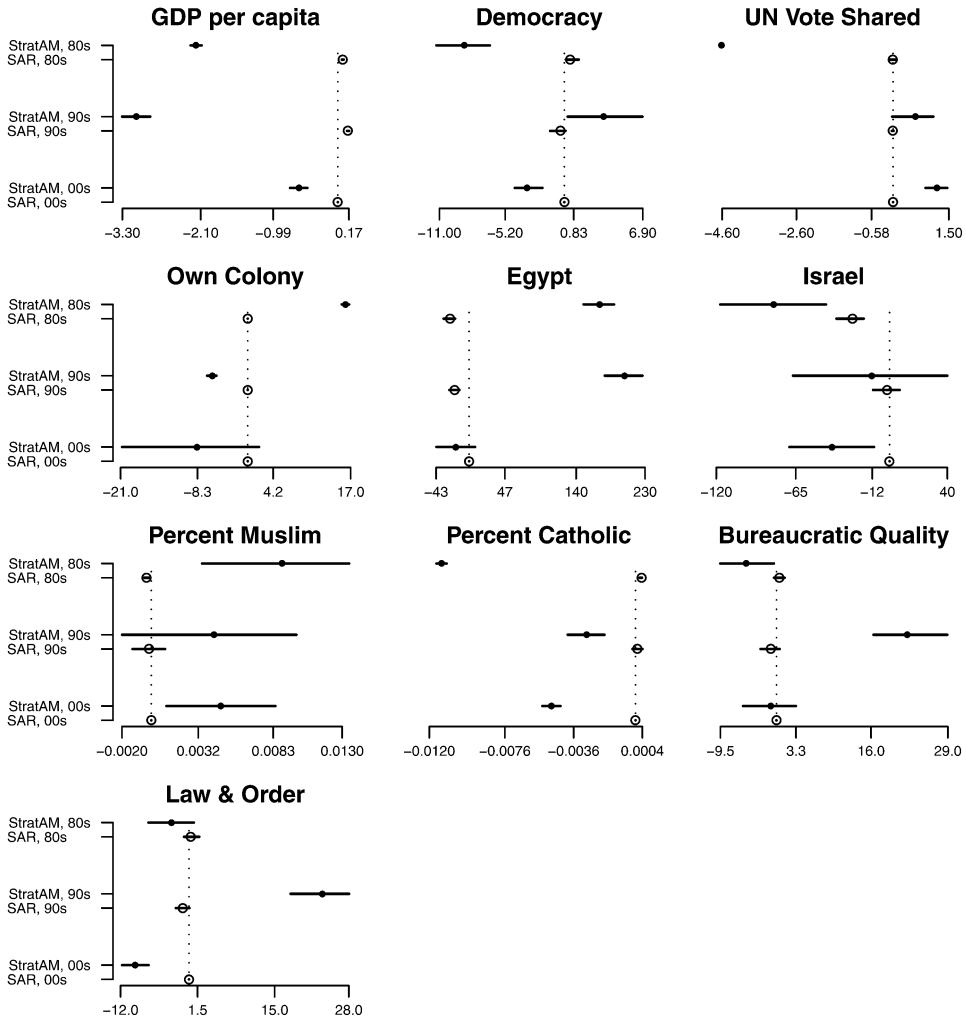



**Fig. 2** Comparison of marginal free-riding effects, StratAM versus SAR.

## 6 Conclusions

My analytical and empirical explorations show how theory can inform the empirical analysis of strategic interconnectivity. The StratAM model offers a unified theoretical and statistical approach to the study of free-riding behavior. Important specification choices of the model, such as interconnectivity weights and actor endowments, follow directly from the theory. In addition, the StratAM model breaks new ground for the systematic testing of the sources of free-riding behavior. Existing workhorse models, such as the SAR, capture aggregate substitution and complementarity effects via a single spatial parameter. Departing from this, the StratAM model allows the analyst to model free-riding behavior with covariates.

The substantive example revealed interesting patterns in the provision of foreign aid. The analysis produced solid evidence that Western foreign aid policy shifted from strategic objectives to a developmental focus in the aftermath of the Cold War. Very little attention has been paid in the aid literature to free-riding effects. The StratAM model is an important tool that will help further this study.

The advantages of deriving a statistical estimator from formal theory come with some cost. The approach places a greater burden on the analyst in considering the theoretical underpinnings of the data-generating process. However, this burden will be easied to the extent that a variety of structural models can serve as toolbox, with each model applying to a different situation. Public good problems are pervasive in many policy areas on the international, regional, and local levels. The StratAM model provides researchers with a tool to systematically explore the sources of free-riding behavior in these varied circumstances.

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## Appendix

**Table A1** StratAM, aid to recipient countries, million dollars

| | *1986–89* | | *1994–97* | | *2002–05* | |
|---|---|---|---|---|---|---|
| *Variable* | *Coefficient* | *Standard Error* | *Coefficient* | *Standard Error* | *Coefficient* | *Standard Error* |
| GDP per capita | −0.533 | 0.0373 | −0.759 | 0.0492 | −0.12 | 0.0219 |
| Bureaucratic quality | −0.0125 | 0.00759 | 0.0548 | 0.00973 | −0.00189 | 0.00479 |
| Law and order | −0.00753 | 0.0064 | 0.0583 | 0.00775 | −0.019 | 0.00303 |
| Democracy | −0.022 | 0.00363 | 0.00836 | 0.00423 | −0.00659 | 0.00215 |
| UN vote shared | 1.82 | 0.0347 | −0.166 | 0.0999 | −0.244 | 0.0425 |
| Own colony | 0.249 | 0.0392 | −0.0754 | 0.0312 | −0.103 | 0.0895 |
| Egypt | 0.455 | 0.0462 | 0.552 | 0.053 | −0.0345 | 0.0302 |
| Israel | −0.189 | 0.0564 | −0.0294 | 0.0741 | −0.0796 | 0.0343 |
| Muslim | 0.231 | 0.0747 | 0.106 | 0.0788 | 0.0964 | 0.0396 |
| Catholic | −0.275 | 0.0196 | −0.0688 | 0.0223 | −0.098 | 0.00995 |
| Constant | −0.392 | 0.0282 | 0.00381 | 0.0742 | 0.315 | 0.0313 |
| $s^2$ | 0.0738 | 0.00295 | 0.023 | 0.000928 | 58.8 | 2.28 |
| # Donors | 15 | | 14 | | 14 | |
| # Recipients | 96 | | 96 | | 96 | |
| Total observations | 1440 | | 1344 | | 1344 | |

**Table A2** SAR, aid to recipient countries, million dollars

| | *1986–89* | | *1994–97* | | *2002–05* | |
|---|---|---|---|---|---|---|
| *Variable* | *Coefficient* | *Standard Error* | *Coefficient* | *Standard Error* | *Coefficient* | *Standard Error* |
| GDP per capita | −0.0361 | 0.0138 | −0.0448 | 0.0102 | −0.0380 | 0.0118 |
| Bureaucratic quality | −0.00225 | 0.00320 | 0.00283 | 0.00208 | −0.00203 | 0.00263 |
| Law and order | −0.00149 | 0.00260 | 0.00300 | 0.00165 | −0.00426 | 0.00168 |
| Democracy | −0.00238 | 0.00150 | 0.000904 | 0.000911 | 0.00108 | 0.00114 |
| UN vote shared | 0.109 | 0.0269 | 0.0257 | 0.0213 | −0.0118 | 0.0207 |
| Own colony | 0.0656 | 0.0117 | 0.0598 | 0.00688 | 0.0782 | 0.00810 |
| Egypt | 0.114 | 0.0226 | 0.0547 | 0.0140 | −0.00199 | 0.0164 |
| Israel | 0.119 | 0.0234 | 0.00536 | 0.0148 | 0.00157 | 0.0179 |
| Muslim | 0.0154 | 0.0268 | 0.00444 | 0.0152 | 0.0268 | 0.0210 |
| Catholic | −0.0162 | 0.00807 | −0.00302 | 0.00464 | −0.0154 | 0.00542 |
| Government consumption | 0.112 | 0.0131 | 0.0872 | 0.00817 | 0.0661 | 0.00753 |
| Constant | −0.0276 | 0.0191 | −0.0306 | 0.0162 | 0.0355 | 0.0155 |
| $\rho$ | 0.0148 | 0.00386 | 0.0211 | 0.00414 | 0.0001261 | $9.37 \times 10^{-5}$ |
| $s^2$ | 0.00732 | 0.000273 | 0.002474 | $5.29 \times 10^{-5}$ | 0.00360 | 0.000108 |
| # Donors | 15 | | 14 | | 14 | |
| # Recipients | 96 | | 96 | | 96 | |
| Total observations | 1440 | | 1344 | | 1344 | |

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