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# Strategic Behavior and the Scope for Unilateral Provision of Transboundary Ecosystem Services that are International Environmental Public Goods*

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ABSTRACT

This paper reports the implications of the current state of the art on the science of strategic behavior for the national treatment of different kinds of international environmental public good. While many environmental public goods are managed through multilateral environmental agreements aimed at building consensus over time (social norms), others are not. Many of the regulating and supporting services identified by the Millennium Ecosystem Assessment, for example, are not subject to agreement. The provision of these ecosystem services depends on the independent actions of many countries. For such environmental public goods it is important to have answers to these questions: Is it necessary to cooperate or coordinate with other countries in their provision? Will unilateral action provide a good-enough outcome? When can individual countries or small coalitions of countries enhance provision of environmental public goods? To answer such questions it is necessary to understand the nature of the environmental public goods, the socio-economic conditions in which they are provided, and the strategic interactions involved. With such an understanding, it is possible to estimate the likelihood that independent voluntary action may produce a 'good enough' outcome.

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## INTRODUCTION

One outcome of the Millennium Ecosystem Assessment (MA) is a deeper understanding of the range of ecosystem services (provisioning, cultural, regulating and supporting services) that affect the wellbeing of people. The MA showed that many ecosystem services are characterized by both publicness (i.e., they are open to all, and their benefits accrue to all), and that they are international in scale (i.e., they benefit people from more than one country) (MA, 2005). These two characteristics complicate their provision. The non-exclusiveness of public goods encourages free riding, while the international scale of many means that cooperative action depends on reaching international agreement. Once provided, the benefits of international ecosystem services accrue to many countries independently of whether those countries have borne any of the costs of provision. The incentive to free ride, and the absence of any global authority means that transboundary environmental public goods are likely to be under-provided or not provided at all (e.g., Conceição, 2003; Barrett, 2007).

Protection of sea areas beyond national jurisdiction, the conservation of genetic information in biodiversity, and mitigation of climate change are all examples of global environmental public goods that are currently underprovided. On the face of it, international coordination or cooperation seems to be a necessary condition for the provision of such public goods. It turns out, however, that while it is true that cooperation is essential for the provision of some environmental public goods, it is not true for all. While many environmental public goods are governed through international agreement, many others are not. Few of the regulating and supporting services identified by the MA (e.g., pollination, natural hazard regulation, soil formation and water cycling) are subject to Multilateral Environmental Agreements (MEAs). Free riding behavior does mean that the outcome of international decisions about the provision of transboundary environmental public goods is generally a non-cooperative one, but it is not always worse than the outcome that could be obtained through cooperation (Sandler, 2004). In fact, non-cooperative action can be quite consistent with the provision of environmental public goods at levels close to the social optimum (Murdoch and Sandler, 2009). Nor are non-cooperation and full cooperation the only options. Coalitions of countries can frequently achieve an outcome that is better than the non-cooperative outcome (Carraro and Siniscalo, 1993).

For emerging environmental public goods, including many of the regulating and supporting ecosystem services, the question of whether countries can be expected to contribute voluntarily to their supply, or should be given incentives to do so, is of extreme practical importance. The general question was analyzed in the early work of Frohlich *et al.* (1975), who discussed the situations where individual voluntary contributions to the provision of public goods were a rational response. Their main argument was that the provision of public goods depends heavily on the production function involved. This argument was further developed by Hirshleifer (1983), Snidal (1985) and, later, by Runge, Sandler, Holzinger and others whose works are discussed below. Much of the emphasis in this literature has been on the conditions that influence the cooperative provision of international public goods, and on the international institutions/treaties established to support that. The social context in which international public goods are provided determines the resulting strategic interactions, and leads to different opportunities for cooperation among countries. As Holzinger (2008) notes, there may be an infinite number of such conditions. However, the literature has focused on six: (a) demand-side properties of public goods, (b) supply aggregation technology, (c) costs and benefits, (d) the number of countries, (e) heterogeneity among countries, and (f) the scope for future interactions. In this paper, we consider the scope for voluntary independent action to enhance the provision of a number of ecosystem services that have the characteristics of international environmental public goods. Using insights from research on the game structures that correspond to different supply aggregation technologies or to different numbers of contributors, this paper identifies where unilateral provision strategies have the potential to be effective for different types of ecosystem services.

The paper is structured as follows. In the next section, we discuss the broad range of outcomes in the existing provision of international environmental public goods. Section 3 characterizes the structure of payoffs corresponding to different supply aggregation technologies, and different threshold numbers of contributors, and discusses the possibility for unilateral action to be effective in each case. Section 4 then illustrates the implications of this discussion using particular examples. It also addresses the complementarity between public goods at different spatial scales. Section 5 offers our conclusions.

## IS COOPERATION NECESSARY FOR THE PROVISION OF INTERNATIONAL ENVIRONMENTAL PUBLIC GOODS?

Since individual countries are primarily concerned with their own national interest, they will only cooperate through bilateral or multilateral agreements if they believe that they are better off (or at least not worse off) because of the agreement (Barrett, 2003; Pearson, 2000). This is, however, a necessary — not a sufficient — condition for agreement. It is a minimum requirement. The agreement should also be perceived as just, i.e., the distribution of the benefits and costs of the agreement should be perceived as equitable or at least acceptable. Given that asymmetry among countries' benefits and costs is the rule not the exception — especially between more and less developed countries — these conditions may require some sort of side payment or benefit sharing scheme as envisaged in the Convention on Biological Diversity or Montreal Protocol. In these two specific cases, countries that benefitted most from biodiversity conservation or ozone layer protection offered side payments to countries that benefitted least. In both cases, side payments provided the inducement needed to assure the participation of countries that otherwise has little incentive to join (Barrett, 2003). In addition, if agreements are to be effective, MEAs should also be self-enforcing. Countries should not only ratify the agreement, but they also should comply with it. Some countries may have strong free riding incentives, i.e., incentives to minimize their costs through non-compliance with their agreement obligations, while they enjoy the benefits achieved by the rest of the signatories. Many agreements accordingly include mechanisms that guarantee that no signatory can gain by free riding on the cooperative efforts of others (e.g., they include punishments for non-compliance). Furthermore, from a global perspective, MEAs are worth negotiating only if countries deliver more than they would have done unilaterally. Experience so far indicates that this is not always the case. The success of MEAs in inducing behavioral changes among signatories varies considerably (Mitchell, 2003). The following range of outcomes in the provision of transboundary environmental public goods through MEAs has been observed:

(i) *Initial agreements are often very close to the non-cooperative outcome.* In many cases, the initial agreement negotiated by parties has been very close to the non-cooperative outcome. Murdoch and Sandler (1997, 2009) show that the Montreal Protocol was initially framed based on the voluntary reductions on CFC levels that the countries were undertaking prior to the treaty taking effect. In the 1985 Helsinki protocol, many signatories countries had substantially reduced their emissions by the time of adoption of the treaty, and studies show that the treaty achieved little with respect to non-cooperative behavior (Murdoch *et al.*, 1997; Ringquist and Kostadinova, 2005). Similarly, the theory of treaty making shows that where large numbers of countries are involved, international cooperation generally succeeds in those situations in which the gap between the cooperative and non-cooperative outcomes is small. The Convention on Biological Diversity and the UN Convention on the Law of the Seas are frequently cited examples. In these cases, while the gains from cooperation in the agreement are small, so is the incentive to defect from the agreement (Barrett, 1994, 2003, 2005).

(ii) *Initial agreements are strengthened over time.* To set against this, there are a number of examples of multilateral environmental agreements involving large numbers of countries that have been strengthened, through successive renegotiation, to offer significantly greater benefits than the non-cooperative outcome. The Montreal Protocol on Substances that Deplete the Ozone Layer (196 state parties), the London Dumping Convention of radioactive wastes (78 state parties), and the International Health Regulations (194 state parties) are the best examples. This is largely because renegotiation in such cases has changed the relative payoff to cooperation over non-cooperation (Sandler, 2004). More particularly, renegotiation has opened up the possibility of reciprocity strategies, as countries compare the immediate gains from defection with the potential loss of future benefits that may result from retaliation (e.g., Axerold and Keohane, 1986; Doebeli and Hauert, 2005; Barrett, 2003, 2005; Dombrowsky, 2007).

(iii) *Agreements between small numbers of parties have stronger enforcement mechanisms than agreements between large numbers of parties.* There are examples of effective multilateral environmental agreements involving smaller numbers of parties, in which the incentive to defect is substantial, but is at least partially countered by effective enforcement mechanisms. The 1995 UN Fish Stocks Agreement allows straddling/highly migratory stocks to be managed on a region-by-region basis through Regional

Fisheries Management Organizations. This has led to the sustainable management of at least some international fish stocks, the Norwegian Spring spawning herring stock being one example (Munro, 2000, 2008).

(iv) *'Best shot' public goods may be provided at close to the social optimum independent of whether they are subject to multilateral agreement*. In addition, there are examples of transboundary environmental public goods that are provided at close to the socially optimal level without any international agreement at all, where the strongest provider/s determine/s the benefits to all. Examples of this are the global information on infectious disease threats offered by the US Centers for Disease Control, the Pasteur Institute in Paris, or the Institute of Virology in Johannesburg. These are primarily driven by national interests in stopping infectious diseases before they arrive, given the impracticality of stopping many infectious diseases at the borders (Zacher, 1999; Sandler, 1997, 2004; Arce and Sandler, 2003).

(v) *Coalitions of members of civil society may also take cooperative action to supply international environmental public goods*. Examples of this include the networks of scientists engaged in the global change research projects, the international private–public partnerships and nongovernmental organizations that fund biodiversity conservation projects, the professional groups that strengthen international infectious disease surveillance; and regional/local–government partnerships on climate change mitigation, such as the Regional Greenhouse Gas Initiative (RGGI) which links the efforts of 10 states in the United States to limit greenhouse emissions[1] (Mitchell, 2003).

## STRATEGIC CONSIDERATIONS IN THE PROVISION OF TRANSBOUNDARY ENVIRONMENTAL PUBLIC GOODS

The decision of any one country to contribute to the provision of a global/regional environmental public good reflects a strategic choice. It depends on that country's expectations of whether other countries will contribute or not, and whether the contribution made by other countries will be affected by its own contribution. In other words, each country's choice depends on how its actions influence the choices and reactions of other countries. Experience with existing MEAs indicates that the propensity to cooperate in the provision of transboundary environmental public goods differs from case to case. This is because the socio-economic and biophysical conditions affecting public good provision vary substantially. Conditions such as the supply technology, the size of the group, the substitutability or complementarity of efforts to provide the public good, all influence the strategic interactions among countries. The results can be very different in different cases. The behavior of countries in supplying different environmental public goods cannot be inferred from the publicness of the good. It depends on the supply technology and the socio-economic conditions within which it is provided (Frohlich *et al.*, 1975; Holzinger, 2001, 2008). The benefits and costs associated with alternative courses of action (whether to contribute or not contribute to the provision of a public good) are

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[1] We thank a reviewer of the paper for providing this example.

represented in the payoff structure. The payoff structure accordingly reflects both the nature of the environmental public good at issue, the socio-economic conditions within each country, and the strategic interactions between them.

Symmetric two-by-two 'games' have traditionally provided a useful tool to investigate the variety of strategic interactions in international affairs, from military-political scenarios, to economic and environmental issues such as trade, finance, fisheries management, or climate change (e.g., Snidal, 1985; Sandler, 2004). In this framework, countries have two options, they must choose between cooperation and defection. The payoff structure for the joint behavior of two identical countries is characterized by $\begin{pmatrix} R & S \\ T & P \end{pmatrix}$, where $R$ is the payoff if both choose cooperation and $P$ is the payoff if there is mutual defection. If the first country defects, the choice of unilateral cooperation on the part of the other gives a reward of $S$. If the first country cooperates, the payoff to defection on the part of the other country is $T$.[2] In this two-by-two setting there are, in theory, 78 potential games.[3] These can be classified into five distinct types of collective action problems (Holzinger, 2003, 2008): (i) coordination problems (where the risk lies in not being able to coordinate action) generally described by 'pure coordination', and 'assurance' games; (ii) disagreement problems (problems of finding an agreement) generally described by 'chicken' and 'battle of the sexes' games; (iii) defection problems (where the risk lies in the incentive to defect from the socially optimal outcome), generally described by 'prisoners' dilemma' and 'asymmetric dilemmas'; (iv) distributional problems (where the risk lies in outcome inequality), generally described by 'rambo' games[4]; and finally (v) instability problems (where the outcome of strategic interactions are unstable), generally described by 'matching pennies' games. There is no systematic information on the empirical frequency of these different games, and the collective action problem involved. In this paper we focus on problems involving defection, coordination and disagreement since they are the most frequently encountered in the management of international environmental public goods.

Figure 1 characterizes different games in the $S$, $T$-plane,[5] and Table 1 summarizes the conditions behind the preference ordering between different games. These games

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2 We borrow this notation from evolutionary game theory in the biology literature where players are identical (e.g., Doebeli *et al.*, 2004; Doebeli and Hauert, 2005).

3 Holzinger (2003) shows that in a two-by-two setting each player can ordinally rank the four potential outcomes in 24 ways, which means that there are theoretically 576 possible combinations of payoffs (assuming strict preference ranking); but only 78 of these combinations were shown to be strategically distinct games. Furthermore, only 56 of these 78 were found to represent some kind of collective action problem. The rest (i.e., 22) are harmony games, in which there is a unique Nash and Pareto-optimal equilibrium, with equal payoffs between players.

4 In rambo games the preference orders differ among the players. Rambo I game is characterized by one player playing a deadlock and the other a pure coordination game; while in Rambo II game, one player plays a game of chicken, while the other plays a game of deadlock. The deadlock game resembles the prisoner's dilemma game but the players prefer joint defection to joint cooperation. Holzinger (2003) argues that rambo games are probably common, although they have not yet received much attention in the literature.

5 Hauert (2001) represents each game in the $S$, $T$-plane, by assuming that $R > P$ and by normalizing the payoff values such as that $R = 1$ and $P = 0$. If $R < P$, *Coordination* and *Defection* are interchanged.

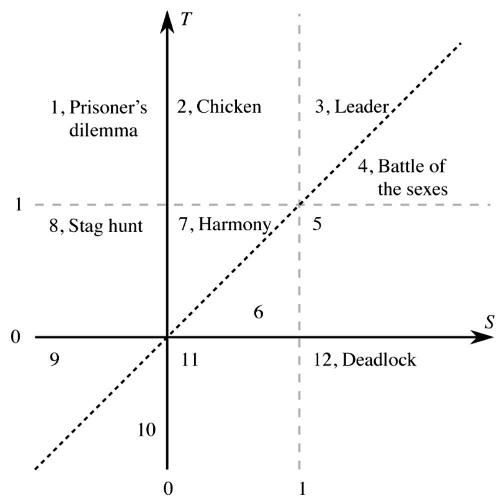


**Figure 1**. Relationship of two-by-two games in the $S$, $T$-plane normalizing payoff values such that $R = 1$ and $P = 0$.

describe situations where there are single/multiple equilibria, distributional and/or coordination issues. A Nash equilibrium results when neither country would unilaterally want to change its strategy choice, i.e., each country is making its best response to the strategies selected by other countries. In the Nash equilibrium, no country can improve its situation by unilaterally switching strategies once the other countries have made their choice. The prisoners' dilemma, for example, has a single dominant equilibrium in which each country chooses not to cooperate regardless of what the other country chooses to do, though both countries would be better off cooperating. Free riding always dominates. This generates a social dilemma. In the harmony game, by contrast, each country is better off cooperating regardless of what the other does. The game does not therefore generate a social dilemma. In harmony games, countries' decisions are unaffected by expectations of the decisions of others, and there are therefore no coordination issues or distributional conflicts.

Other games such as the assurance and battle of the sexes games are characterized by multiple equilibria, but coordinated actions are preferred by both countries to failure to coordinate. They therefore differ from games such as prisoners' dilemma or 'chicken' that do not have any coordination equilibrium. Coordination equilibria are stronger than Nash equilibria. No country can improve its position by changing its response. Nor can it be made better off by making a different response from the other country. Neither the 'assurance' nor the 'battle of the sexes' games represent pure coordination games. In pure coordination games, each country would be indifferent between coordinated equilibria. However, both can be classified as coordination games because coordinated actions are preferred to non-coordinated actions. In the battle of the sexes games, countries do not agree which equilibrium is better. In assurance games, while each country prefers

**Table 1**. Summary of different strategic interactions based on potential payoff structures.

| | Strategic interactions |
|---|---|
| Prisoners' Dilemma | This occurs where two countries would benefit most if they were to cooperate in the provision of a public good, but where their individual interest leads them to defect. Examples include the exploitation (or pollution) of international common pool resources. |
| Chicken (also called Snowdrift)[6] | This occurs when countries prefer not to contribute towards an international environmental public good, but where the worst possible outcome is one in which no country contributes. This leads countries to contribute if they believe that others will not. Notice that if the cost of acting unilaterally is too high, mutual defection situation would be preferred and this situation would be characterized by the prisoners' dilemma. |
| Assurance (also called Stag Hunt) | If all countries cooperate in the provision of an international environmental public good they get the outcome that is best for each. If one decides not to cooperate it makes no difference what others do — the effort will fail. The worst outcome is if one country cooperates and the other does not, for their effort is wasted.[7] |
| Battle-of-the-sexes | This occurs where countries have different preferences about how to provide an international environmental public good, but each would rather adopt the provision strategy chosen by the other than to adopt its preferred provision strategy on its own. |

the social benefit secured through cooperation, there is a risk that the other country will fail to cooperate leading to a situation where the public good is not provided and unilateral efforts are wasted. The chicken game is characterized by a strong temptation to defect, but where unilateral provision of the public good is preferred to a situation where there is mutual defection. This generates multiple equilibria, each of which might have quite distinct distributional implications. It arises because the countries have conflicting preferences with respect to the potential equilibria. There are both coordination issues and distributional conflicts between countries over which equilibrium should be chosen.

There is a strong temptation in the literature to describe most environmental public good situations as prisoners' dilemmas, in which the Nash equilibrium is the worst outcome from a social perspective. However, while many international environmental public good problems are indeed prisoners' dilemmas, many more are not (e.g., Runge, 1984; Taylor and Ward, 1982; Cornes and Sandler, 1996; Aggarwal and Dupont, 1999; Holzinger, 2003; McAdams, 2009). In what follows, we consider where the coordination

[6] The equivalent of the chicken game in evolutionary biology is termed the Haw-Dove game (Rasmusen, 2001).

[7] Skyrms (2001) is citing Jean-Jacques Rousseau's book "A Discourse on Inequality".

and distributional issues involved in international environmental public good provision are best represented by other game structures, and hence where there is scope for assuring their provision without having to rely on cooperation between large number of nation states.

### Technology of Public Good Supply

The critical questions here are: first, how the 'technology' of transboundary environmental public good provision influences the structure of payoffs and, second, how the structure of payoffs affects the level of provision, and the distribution of benefits. The technology of public good provision[8] describes public goods in terms of the way in which contributions by individual countries affect their provision. The most common technologies involve 'step', 'best-shot', 'better-shot', 'weakest-link', 'weaker-link', 'summation' and 'threshold' public goods.

Public goods that can only be provided if a minimum amount has been contributed to their production, and that do not increase in quality or quantity by further efforts are known as step or lumpy goods. A bridge would be an example of a step public good (since half a bridge is no bridge at all).[9] Common international environmental public goods that fall into this category include (a) the construction and maintenance of defensive or protective measures, such as coastal defenses or dikes, (b) the establishment and maintenance of conservation bio-corridors between the sub-populations or sub-communities of a meta-population or meta-community, or (c) eradication of an infectious disease such as small-pox or an invasive pest. The benefits offered by investment in the public good are zero unless the defensive barrier, the bio-corridor or the eradication program is complete.

Whether step public goods are efficiently provided depends on the responsibility that each country has for its provision. In a number of important cases the benefits to all countries depend on the efforts of just one country. If that country is the most effective provider, the public good is described as 'best-shot'. If that country is the least effective provider, it is described as 'weakest-link'. Hirchleifer's (1983) classic example of a best-shot technology is a nuclear defensive nuclear shield, where all countries in a defensive pact depend on the capacity of the country with the most effective shield. His example of weakest-link technology is where a defensive barrier, a dike say, is maintained by a number of communities. The protection of all communities is limited by the protection provided by the weakest link, i.e., the lowest or least well-maintained section of the dike. In this case, contributions are neither substitutes for each other, nor are they additive (i.e., a well-maintained section of dike cannot compensate for a poorly maintained one). Less strict aggregation technologies are called weaker-link and better-shot. Under the weaker-link (better-shot) technology, the country with the smallest (largest) effort has the greatest influence on the production level of the public good, followed by the country with the second smallest (largest) contribution, and so on. Weaker-link and better-shot

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8 Term coined by Cornes and Sandler (1996).

9 Example provided in Hampton (1987), p. 249.

public goods are recognized to be more common in international environmental public good problems than the more extreme weakest-link and best-shot cases (Arce and Sandler, 2001). Examples of weaker-link technology include curbing invasive pest species spread, where the inspection, sanitary and phytosanitary efforts of individual countries determine the likelihood that the species will be reintroduced. Countries efforts' to avoid smuggling of endangered species is another weaker-link example. An example of better-shot supply technology would be international warning systems against natural disasters, when efforts beside those of the most effective provider also add to the international benefits of public good provision.

At the other end of the spectrum are summation (or incremental) goods for which the benefits to all countries depend on the sum of the efforts of each country. For such goods every country's efforts contribute to the quantity or quality of the good. The most widely used example of an international summation environmental public good is the mitigation of climate change through carbon sequestration. However, many transboundary atmospheric and water pollution problems are similar (e.g., Dombrowsky, 2007). The benefit of abatement to all depends on the cumulative effect of individual efforts on the aggregate pollution burden. Other examples of international environmental public goods that may be in this category include watershed protection, flood control, and habitat conservation. In these cases, the benefits offered scale with the area protected. Unlike best-shot public goods, since every hectare provided confers benefits, free riding activity by any one country imposes costs on all countries, and every country has an incentive to free ride.

Between step and summation public goods are a range of mixed cases. Many of these fall under the category of threshold public goods. As with step goods, threshold goods yield no benefits below a certain scale of provision, but unlike step goods, the marginal value of subsequent contributions may be positive — they add to the benefits conferred by the public good. The control of infectious diseases falls into this category. The long-term control of infectious diseases requires that the basic reproduction ratio (R0) — the number of individuals infected by each infected individual — is brought below 1. The level of effort required to do this represents a threshold level of effort. Beyond that threshold, however, there will still be benefits to further reductions in R0.

Threshold public goods exist because many environmental systems can exist in multiple stable states, and the benefits they provide depend on the state they are in. It follows that crossing thresholds may be a source of both benefits and costs. Actions that cause a system to flip from a desirable state into an undesirable state will be associated with a sudden decrease in net benefits. Indeed, in the environmental literature, 'threshold goods in reverse' are frequently studied, and are used to justify the use of safe-minimum standards. So, for example, the benefits that derive from a water body in an oligotrophic (well oxygenated) state may be marginally reduced with increasing levels of organic pollution (biological oxygen demand), but will collapse completely at the point at which the system flips from an oligotrophic into a eutrophic (hypoxic or anoxic) state (Carpenter and Cottingham, 1997). Conservation thresholds include critical minimum population sizes, or critical habitat sizes of endangered species. Reversing the degradation of systems that have flipped through stress from one state into to another may well involve hysteresis — that the stressor has to be reduced well beyond the level at which the flip originally occurred — but will still be associated with threshold effects. Where the change is irreversible, as in the case of species extinctions, the costs of exceeding the threshold may be extremely high.

### The Number of Countries, the Technology of Public Good Supply and Strategic Interactions

Depending on the technology of public good supply, countries engaged in the provision of international environmental public goods can adopt widely differing strategies (e.g., Hampton, 1987; Sandler and Sargent, 1995; Holzinger, 2001; Sandler, 2004; Barrett, 2007). Generally, summation public goods are associated with the strategies expected of prisoners' dilemma and chicken games; best-shot public goods with chicken games; and weakest-link public goods with assurance games (Sandler, 2004, pp. 60–68). While the technology of public good supply and the effect of the number of contributors are independent properties of international environmental public goods, the combination of the two will affect the strategic behavior of individual countries. Common problems that necessitate a minimal set of cooperators can result in different games, altering the scope for voluntary independent actions in international provision of environmental public goods. In what follows we consider the joint effect of these properties on the game structure, and the implications it has for unilateral action.

Consider a summation technology problem, such as carbon abatement/sequestration (e.g., Holzinger, 2001; Barrett, 2007). All contributors' efforts are perfectly substitutable, and a decrease in the contribution of one nation can be made up by increased provision by the others. We have observed that summation technology is linked to prisoners' dilemma, where the structure of payoffs may be such that $T > R > P > S$ (see Figure 1 and Table 1). The social optimum will hold if all the countries contribute, but the dominant strategy for each country is to defect (not to contribute) because this is the best response independently of the choice of others. The total reduction in emissions is what determines the level of provision of the public good, i.e., preserving or restoring the atmosphere. If the unitary costs of decreasing emissions are higher than unitary benefits to each country, the dominant strategy is not to contribute. Additive public goods can, however, also result in a chicken game. If the consequences of inaction lead to dire consequences, this gives the richest countries an incentive to act (Sandler, 2004).

Where individual contributions are not substitutes, contributions by different countries will have a different additive impact on the overall level of provision. This is called a weighted-sum technology. It occurs, for example, in local air pollution (e.g., sulfur dioxide, nitrogen oxides, organic compounds), where a country's self pollution and imported pollution may depend on factors such as wind direction, the country's location, and its size. The game played is determined by country-specific attributes, and these also determine its incentive to contribute (Sandler, 2008).

For best-shot supply technologies, strategic interactions have the structure of a chicken game (Hirshleifer, 1983; Sandler, 2004). Two conditions are expected to hold. First, in no case is the individual benefit from acting unilaterally higher than the total costs of providing the public good (Hampton, 1987). Otherwise, it would always be in the interest of a country to act independently. Second, countries are assumed to be able to produce the good interchangeably, i.e., public goods provided by different countries are assumed to be perfect substitutes (Holzinger, 2001). The structure of payoffs in the chicken game accordingly takes the form: $T > R > S > P$ (see Figure 1 and Table 1). Thus, each country's first best response would be to do nothing, and to let the other countries produce the public good. Next best would be a situation where countries jointly contribute to the provision of the public good, splitting the costs between them. However, if no country contributes, then unilateral provision is still preferred to the case where the good is not provided at all. In this case, the pursuit of self-interest, without regard to whether the other countries would cooperate or not, leads to joint international gains. The multiple Nash equilibria in this strategic game are characterized by unilateral actions, where one country or set of country/ies contributes and others free ride. Nevertheless, provision in such cases is likely to be sub-optimal from a global perspective (Lipnowski and Maital, 1983).

It follows that for problems with this general payoff structure, international cooperation may not be necessary to realize the global public good at some level. At the same time, the number of countries contributing and the level of provision of the global benefits depend on the problem at hand. Consider the work of the US Centers for Disease Control (CDC), which track contagious diseases worldwide (Sandler, 2004). Irrespective of the actions of other countries, the US acts unilaterally to generate this information because if diseases can be contained locally they will not threaten the US. Moreover, by doing this, the CDC promotes world health, so joint global gains are independent of cooperation. Similar conclusions can be drawn for the work of the Pasteur Institute in Paris, or the Institute of Virology in Johannesburg. In such cases, as mentioned above, cooperation is not essential for the provision of global benefits. The country/ies with the most to gain from provision of the pubic good will, by default, opt to provide it.

Note, though, that the chicken game, like the prisoners' dilemma, generates a social dilemma. Since for each country $S > P$ (i.e., payoffs from unilateral action are better than those from mutual defection), each would prefer to free-ride on the contributions by other countries. Therefore, there is the risk of mutual defection, where the public good is not provided at all, and this is socially and individually the most undesirable situation. Given that it is in the best interest of individual countries not to act, it may be necessary to negotiate side payments as each country pushes others to act. Thus, the relevant question is to decide which of several free-riding equilibria provides the best outcome — since this is superior to mutual non-cooperation.

Environmental public goods characterized by weakest-link technologies, such as the global eradication of an infectious disease, require contributions from all countries, but nothing is gained by providing more than the country making the smallest contribution. This calls for a matching strategy (Hirshleifer, 1983). In contrast to best-shot public goods, the contributions by different countries are not interchangeable. In other words, all contributions are necessary, and whether they are substitutes or not makes no difference (Holzinger, 2001). This technology leads to a coordination assurance game, where the structure of payoffs is such that $R > T > P > S$ (see Figure 1 and Table 1). In the two country game, there are two Nash equilibria, full cooperation or full defection, but only the first is Pareto-optimal. In the language of the original stag hunt game, it is best to hunt stag if the other party hunts stag and it is best to hunt hare if the other party hunts hare. The country choosing not to cooperate faces no risk, since their payoff does not depend on the action chosen by the other country, but they forego the potential payoff associated with cooperation. There is a strong preference to cooperate provided that others do the same, i.e., what it is rational for one country depends on their expectations about what others will do. Unilateral efforts will be wasted. So in the example of the eradication of an emerging infectious disease either all countries cooperate and contribute to the eradication of the disease or all will fail. Unilateral action by any one country cannot prevent the disease from spreading to their territory from neighboring countries. That said, unilateral action by one country can increase the prospects of a cooperative outcome, if it induces other countries to act (Sandler and Sargent, 2001).

It follows from the best shot problem, that a critically important factor in the provision of international environmental public goods is the minimum number of contributors, $m$, needed for provision of the good in an $n$ country case (where $m \leq n$) (Hampton, 1987; Sollars, 2003). This minimum size group condition can be interpreted differently depending on the supply aggregation technology: (a) In the best-shot case it implies that $m = 1$, a single country is sufficient to secure the public good. (b) Symmetrically, in a weakest-link public good, it requires that $m = n$, the matching cooperative behavior of all countries is needed to secure the public good (Holzinger, 2001). (c) In the threshold supply technology, $m$ defines the *threshold* of contributors (or provision level), which must be exceeded for the benefits to be received. We note that thresholds of this type may be the result of the institutional design of treaties, e.g., agreement on the number of ratifying parties needed before the agreement comes into force (Sandler, 2008).

Minimum size requirements of this kind induce three potential types of strategic behavior. In an $n$ country context with a minimum number $m$ of contributors, it generates a chicken game: each country would prefer others to carry the cost of providing the public good. This has significant implications for unilateral action. Consider, for example, a conservation problem involving protection of an endemic endangered species in a wilderness area that requires collaboration between at least two countries to assure a protected area of sufficient size. We may suppose that the countries with jurisdiction over the wilderness area are able to produce the public good interchangeably. The problem with three countries is illustrated in Table 2. Following the reasoning of Hampton and Sollars, each country would most prefer a situation where it does nothing, and enjoys the aesthetic and recreational benefits of the endemic species in the protected area funded by the remaining countries ($T$). Their second choice would be where all three countries split the costs of conservation ($R$), which dominates the case where they share the cost with one other state only ($S$). However, this last option is preferred to a situation where the wilderness area is not provided at all because no two countries are able to agree on its provision ($P$). In this case, unilateral action yields the worst possible outcome.[10]

[10] This conclusion would not hold if we assume that cooperation when nobody does is equally preferred to cooperating when all cooperate (which implies changing 5 for 2 in Table 2). The strategic interaction among countries would be still characterized as a chicken game (Sollars, 2003).

**Table 2**. Three country chicken game with a two country threshold.[a]

| | Countries 2, 3 | | | |
|---|---|---|---|---|
| Country 1 | C; C | C; D | D; D | D; C |
| C | 2,2,2 | 3,3,1 | 5,4,4 | 3,1,3 |
| D | 1,3,3 | 4,5,4 | 4,4,4 | 4,4,5 |

*Source*: Sollars (2003).[11]
[a] C and D refers to cooperate and defect, respectively. Nash equilibria are shown with one underline, and coordination equilibria with a double underline.

Unilateral action would mean that the species would still be driven to extinction. So while there exists a coordination equilibrium in which all defect, it is less preferred by all than either of the other Nash equilibria (where all contribute, or where two countries contribute, and one free-rides). Given that each country is always better off free riding on the others, there is a distributional conflict to be addressed. If countries are not symmetric, those with the greatest benefits may combine efforts to achieve the threshold. A common example is cooperation between neighboring countries in fighting diseases or pests (Sandler, 2008).

This may convert to a different game if not all the countries can share the work. More particularly, if there is no good way for the group of countries involved to cooperate in producing the public good, strategic interactions will have the characteristics of the battle-of-the-sexes game (Sollars, 2003). This may occur in our conservation example if the protected area can be split into viable physical units but there are more countries wanting to contribute than there are viable units; or if there are a variety of ways in which individual countries could combine resources to create viable units (Hampton, 1987). Each country might prefer that endangered species in the transnational area be protected, but if coordination between all countries is ruled out, and if the two countries that contribute bear the costs (i.e., $T > R$), then coordination may not occur and conservation could fail. Table 3 illustrates this battle of the sexes problem for the three country case with three salient coordination equilibria, each preferred by the country that does not contribute.

Another more specific case involving environmental public goods with a minimum size requirement is where a number of countries are charged with providing the environmental public good (Sollars, 2003). Global community pressure or scientific capacity might determine which countries are charged in this way. For each country of this group

[11] Sandler's (2008) Figure 4(b), which represents a summation technology with a threshold of three contributors in a five country case, has equal ordering of payoffs (chicken game) and are shown in Table 2.

**Table 3**. Three country battle of the sexes game with a two country threshold.[a]

| | Countries 2nd, 3rd | | | |
|---|---|---|---|---|
| Country 1st | C; C | C; D | D; D | D; C |
| C | 3,3,3 | 2,2,1 | 3,3,3 | 2,2,1 |
| D | 1,2,2 | 3,3,3 | 3,3,3 | 3,3,3 |

*Source*: Sollars (2003).
[a] C and D refers to cooperate and defect, respectively. Nash equilibria are shown with one underline, and coordination equilibria with a double underline.

cooperation is preferred to the alternative in which the group fails to form (i.e., $R > T$). Defection by any one country can cause the group to fail, and the worse outcome is for a 'short-handed' group to waste resources without achieving provision of the public good. In this case there are two equilibria: (i) where all selected countries join the group or (ii) where no one does. All countries prefer the first to the second outcome, as Table 4 illustrates for a three-country setting with a minimum group of three countries. This induces the strategic behavior associated with an assurance game, where coordination among the chosen countries is required to achieve international gains through the environmental provision. However, note that if the selected countries believe that a subset of them can provide the good, then it is once again a chicken game, where the equilibria involve free riding by some. The assurance game characterizes the problem of coordination of efforts among the countries within a group of minimal-size — the size necessary to make cooperation through a treaty worthwhile (Sandler and Sargent, 2001). It can also arise if there is a threshold high enough that requires the contribution of all nations involved in the environmental problem (Sandler, 2008). An example of this might be joint investments in pollution control efforts in internationally shared lakes, where all countries involved are required to invest in wastewater treatment for the lake to reach bathing water quality (Dombrowsky, 2007).

The strategic interactions associated with weaker-link and better-shot public good supply technologies have been analyzed as continuous games (Arce and Sandler, 2001). The properties of these technologies imply that unilateral actions by one country can generate positive global benefits by contributing to the increase of the transnational public good, even if other countries do not make any contribution. In better-shot cases, the greatest marginal gain from unilateral actions is derived from the country already making the highest overall level of contribution. While in weaker-link problems, the greatest marginal impact on overall level of provision is derived from unilateral actions by the country making the smallest effort. The strategic interaction among countries involved in the supply of a better-shot public good is still that of the chicken game (Arce and Sandler,

**Table 4**. Three country assurance game with a two country threshold.[a]

| | Countries 2nd, 3rd | | | |
|---|---|---|---|---|
| Country 1st | C; C | C; D | D; D | D; C |
| C | 1,1,1 | 3,3,2 | 3,2,2 | 3,2,3 |
| D | 2,3,3 | 2,3,2 | 2,2,2 | 2,2,3 |

*Source*: Sollars (2003).[12]
[a]C and D refers to cooperate and defect, respectively. Nash equilibria are shown with one underline, and coordination equilibria with a double underline.

2001). The dominant equilibria are characterized by a degree of free-riding, where both countries supply the good but one country's contribution is higher than the other.

### Unilateral Contributions to International Environmental Public Goods

What does this mean for voluntary unilateral action to enhance provision of transboundary environmental public goods? We have seen that summation public goods are characterized by the prisoners' dilemma game if the individual benefits of provision are lower than the individual costs of provision (e.g., Holzinger, 2001; Sandler, 2004). In such cases, countries have a dominant strategy — to free-ride on provision of the public good by others. In cases where countries value the public good more than the cost of its provision, i.e., the benefits of individual provision are higher than the costs, the strategic options change to those associated with the harmony game. In such cases contributing to the public good production is the best strategy, i.e., it generates the highest payoff, independently of the actions of the other countries. In fact, non-contributing countries will be better off by changing their strategy.

For best-shot, better-shot, or weaker-link (with decreasing diminishing returns) environmental public goods, there are no dominant strategies, and the chosen strategy depends on the action of other countries. In such cases, countries prefer to take unilateral action rather than face a situation without the environmental public good, but find it more profitable to defect once any other country or group of countries guarantee its provision. That is, the strategic options are those of the chicken game.

For weakest-link or threshold public goods (with 'selected' countries or minimum size countries equal to countries involved), countries would prefer not to contribute unless they expect a sufficient number of other countries to contribute as well. Below

[12] Sandler's (2008) Figure 4(c), which represents a summation technology with a threshold of five contributors in a five country case, has equal ordering of payoffs (assurance game) as those shown in Table 4.

that number of co-contributors, it is in the best interest of the country to defect. Above that number it is in the best interest of all to join the coalition of cooperators, and to contribute to the environmental public good provision in the assurance game. In such cases a country may be induced to take the lead if it has strong enough expectations that other countries will follow.

For threshold public goods or step public goods with minimum group size or minimum level of provision there is no payoff to independent action if the minimum group size requirement is not met. But nor is there any additional payoff to contribute, once other countries have provided the minimum amount of the public good. Once again, this induces strategic behavior associated with the chicken game, but with the additional complication that independent unilateral action may mean wasted resources. Only if the contributions of other countries aggregate to some level, or only if a sufficient number of other countries have agreed to contribute, will a country make a decision to contribute itself. In this situation, a group of countries may emerge that are able to sustain cooperation and defection of third parties may have no significant effects on the global provision of the public good.

## IMPLICATIONS FOR THE PROVISION OF TRANSBOUNDARY ECOSYSTEM SERVICES

We now consider what this means for the provision of a number of ecosystem services that have public good characteristics (identified in Table 5). This table (a) identifies the ecosystem services at issue and the spatial scale of the benefits they yield, (b) characterizes them in terms of the structure of payoffs and properties of public goods — whether they are pure or impure, club goods, open-access, additive, best shot, weakest link, etc., (c) describes the strategic problem in each case — prisoners' dilemma, chicken, assurance, etc. and (d) identifies the system of governance applying to their provision.

We are especially interested in the case where the strategic interests of individual countries lie in the provision of some ecosystem service independently of what other countries may be doing. There are widely differing types of public good involved. Many are supplied as joint products, some of which are complements, others substitutes. Many offer distinct benefits at different scales. Some are subject to formal agreement, others are not. Moreover, while some are defined by the biophysical properties of the system, others are socially constructed. That is, they are non-exclusive not because of their biophysical properties but because of a set of socially constructed access rules.

There are few environmental public goods amongst the Millennium Ecosystem Assessment 'provisioning services' (MA, 2005), yet all provisioning services depend on environmental assets that are collectively owned. They are accordingly affected by the access rules governing those assets. Collectively owned common pool resources are part of the 'environmental infrastructure' that supports the production of foods, fuels and fibers. More 'cultural services' than 'provisioning services' are public goods, especially those having aesthetic appeal or religious significance, and their supply — through conservation, preservation or legal protection — generally lies outside the market. World Heritage Sites, international wildlife parks or reserves, and *ex situ* global collections all

**Table 5**. Ecosystem services that are international environmental public goods.

| Environmental action | MA ecosystem service and geographic scale | Publicness and supply technology | Strategic problem | Current governance |
|---|---|---|---|---|
| *Conservation of common pool resources* | | | | |
| Conservation of endangered species | Cultural, local to global | **Pure public good. Additive** (endangered species census or the size of an ecosystem left aside for conservation); **better shot** (protection of a given endangered species); **weakest/weaker link** (controlling illegal trade; or conservation of a metapopulation); **threshold** (maintaining a minimum size habitat, or corridors) | Additive: prisoners' dilemma game if $b_i < c_i$ or chicken game if no action can have disastrous consequences. Better shot: chicken game. Weaker link: assurance game or chicken game if strong diminishing returns. Threshold: assurance game if countries in minimum size group known a priori, otherwise chicken game or battle-of-the-sexes. | Local-national regulation, PA, MEA |
| Conservation of genetic information | Provisioning Cultural, local to global | **Pure public good. Additive** (in-situ conservation policies), **better shot** (gene banks) | Additive: prisoners' dilemma game if $b_i < c_i$ or chicken game if no action can have disastrous consequences. Better shot: chicken game. | Local-national regulation, PA, MEA |
| Conservation of harvested wild living resources | Provisioning, regional-global | **Common pool resource. Additive** (harvesting quotas in fisheries) | Additive: Prisoners' dilemma game or chicken game if no action can have disastrous consequences. | Local-national regulation, PA, MEA |
| Protection of sites of special scientific interest, religious or cultural significance | Cultural, local to global | **Joint product. Best, better shot, weighted sum** (word heritage protection) | Best, better shot: chicken game. Weighted sum: harmony game — when joint products include significant excludable provider-specific benefits. | Local protection, PA, SPP |

(*Continued*)

**Table 5**. (*Continued*)

| Environmental action | MA ecosystem service and geographic scale | Publicness and supply technology | Strategic problem | Current governance |
|---|---|---|---|---|
| *Control of human, animal and plant health* | | | | |
| Management of infectious disease | Regulating, local to global | **Impure public good. Weaker, weakest link** (monitoring and limiting a disease outbreak); **threshold** (getting basic reproduction ration below one). | Weaker, weakest link: assurance game or chicken game if strong diminishing returns. Threshold: assurance game if countries in minimum size group known a priori, otherwise chicken game or battle-of-the-sexes. | Local-national regulation, MEA |
| Quarantine, port inspections | Regulating, local to global | **Impure public good. Weaker, weakest link** | Weaker, weakest link: assurance game or chicken game if strong diminishing returns. | Local-national regulation, MEA |
| Pest control | Regulating, local to global | **Impure public good. Weakest, weaker link** (limiting the spread). | Weaker, weakest link: assurance game, or chicken game. | Local-national regulation, MEA |
| Eradication of invasive species | Regulating, local to global | **Impure public good. Weakest, weaker link** (eradication and containment of any further spread); threshold | Assurance game, or coordination game, if it does not pay a country to eliminate as long as the invasive species exists abroad but it does pay when it has already been eliminated abroad. | Local-national regulation, MEA |
| Vaccine development | Regulating, local to global | **Pure public good. Best, better shot** (HIV/AIDS vaccination) | Best, better shot: chicken game. | Local-national regulation, MEA |
| Information about disease/pest/invasive risks | Regulating, local to global | **Pure public good. Better shot** (building a pest database), Weakest link (information sharing network) | Better shot: chicken game; Weakest link: assurance game. | Local-national regulation, MEA |

(*Continued*)

**Table 5**. (*Continued*)

| Environmental action | MA ecosystem service and geographic scale | Publicness and supply technology | Strategic problem | Current governance |
|---|---|---|---|---|
| *Natural hazard protection* | | | | |
| Coastal protection against storms | Regulating, local to regional | **Pure public good. Weighted sum** (where coastal barriers protect hinterland), **weakest link** (where protective dykes need to be intact to deliver benefits) | Weighted sum: a variety of games may be possible depending on the weights; harmony game if provider-specific benefits are large. Weakest link: assurance game. | Local-national regulation |
| Flood protection | Regulating, local to regional | **Pure public good. Additive, weighted sum** | Harmony, prisoner's dilemma or battle of the sexes, if countries differ in the preferred location of a joint action (e.g., building a dam). | Local-national regulation |
| *Management of atmospheric quality* | | | | |
| Regulation of air quality, control of $NO_X$, $SO_2$ emissions | Regulating, local to regional | **Impure public good. Weighted sum** | A variety of games may be possible depending on the weights. Weights associated with $SO_2$ seem to characterize a harmony game (Helsinki Protocol). | Local-national regulation, MEA |
| Stabilization of ozone | Supporting, global | **Pure public good. Additive** (reducing use of ozone destroying chemicals) | Harmony game for the core producers. An EPA report showed benefits > costs for any country acting alone. The pursuit of self-interest without regard to the actions of others leads to unilateral action. | MEA, EM, PES |
| Carbon sequestration | Supporting, global | **Pure public good. Additive** (reducing $CO_2$ emissions) | Prisoners' dilemma game or chicken game. | MEA, EM, PES |

(*Continued*)

**Table 5**. (*Continued*)

| Environmental action | MA ecosystem service and geographic scale | Publicness and supply technology | Strategic problem | Current governance |
|---|---|---|---|---|
| *Management of water quality* | | | | |
| Coastal protection | Regulating, local to regional | **Additive** | Prisoner's dilemma game or chicken game. | Local-national regulation, MEA |
| Watershed or shared lake protection | Regulating, local to regional | **Joint products. Additive, Weighted sum, Weakest link** (setting standards) | Additive: prisoner's dilemma, chicken game, or assurance game if economics of scale from join water treatment. Weighted sum: a variety of games may be possible depending on the weights. Weakest-link: coordination game (pure coordination, battle-of-sexes, assurance). | Local-national regulation, MEA |
| Nutrient flows | Supporting, local to regional | **Additive with threshold** | Chicken or battle of the sexes. | Local-national regulation, MEA |

PES, payments for ecosystem services; MEA, multilateral environmental agreement; SPP, state-private partnership; PA, Protected Area. Note: Further details on these international actions can be found in the literature cited along this review, e.g., human, animal and plant health, and air quality (Sandler, 2004; Barrett, 2003, 2007), species conservation (Holzinger, 2001), and water management (Dombrowsky, 2007).

involve international collective action. These are often best or better shot problems, implying that the benefits to those affected by the public good are unilaterally provided by individual countries or consortia of countries best able to fund provision of the good.

The 'regulating services' are frequently supplied as an international public good. In agriculture, for example, the regulatory benefits offered by crop genetic diversity operate all the way from the local to the global scale. Supply technologies for the regulating services can take different forms. While disease control is frequently a weakest or weaker link supply public good, the protection offered by redundancy in functional groups of species (a regulating service) or by flood control actions are generally additive (Sandler, 2004; Barrett, 2007; Holzinger, 2001; Dombrowsky, 2007). The MA 'supporting services' include the processes of the atmosphere, the hydrosphere and the biosphere, and offer benefits that extend all the way from the local to the global scale. While the supply technologies for public goods of this type are generally additive, they operate at very different scales. Mitigation of climate change through carbon sequestration or reduced carbon emissions is additive at the global scale. Mitigation of water pollution risks through reductions in nitrate emissions is additive at much more local scales.

More important for the incentive countries to provide environmental public goods is the fact that particular land uses may support the provision of environmental public goods at multiple scales (Perrings and Gadgil, 2003). Biodiversity in tropical forests, for example, yields a set of private benefits in the form of timber and other products including medicinal plants, hunting, fishing, recreation and tourism. But tropical forests also have value for their role in the provision of a number of global public goods, including carbon sequestration and genetic information, as well as a number of local public goods, including the regulation of the hydrological cycle, microclimatic regulation and so on. Similarly, conservation of watersheds for the supply of clean water also provides habitat for endangered species.

In fact, the complementarity between distinct environmental public goods associated with forests is the basis for the growing enthusiasm for the Reduced Emissions from Deforestation and forest Degradation in developing countries (REDD) scheme (Myers, 2007; Miles and Kapos, 2008; O'Connor, 2008). In the REDD case, for example, carbon sequestration is thought to be produced jointly with biodiversity and watershed protection. Yet unless public goods are perfect complements in production, the development of a mechanism to assure supply of one will not assure supply of another. As it happens, the complementarity in production between carbon sequestration and other ecosystem services is not yet established (Jackson *et al.*, 2005), and the pattern of protection implied by distinct ecosystem services is quite different (Chan *et al.*, 2006). But where the provision of one public good is a by-product of the provision of another, the costs of provision can be very low.

The incentive to individual countries to free ride on others is greatest in the case of additive supply technologies, and least in the case of weakest link technologies (Holzinger, 2001). The incentive to individual countries to act unilaterally is greatest in the case of best-shot supply technologies, and least in the case of summation technologies. However it also depends on the net costs and benefits of public good provision. The joint production of public goods can significantly reduce the cost of their provision. Whether the public good is 'pure' or 'impure' — whether it yields any privately capturable benefits in addition to its non-capturable public benefits — can just as significantly increase the benefits of their provision (Sandler, 1997, 2004). Biodiversity conservation, for example, is an impure global public good (a public good yielding both nationally capturable benefits as well as a set of non-exclusive and non-rival benefits to the global community). The greater the locally capturable benefits of environmental public good provision, and the greater the complementarity between these locally capturable benefits and the benefits to the wider community, the greater will be the incentive to provide the international environmental public good independent of what choices are made by other countries.

Several factors turn out to be important in determining the payoff to local provision of public goods that confer wider benefits. The most important of these are the rules of access to the resources involved. Common pool environmental resources that are open access but also scarce (the social opportunity cost of their use is not zero) are systematically overexploited. Environmental public goods that are public only by virtue of the access rules that govern their use are especially vulnerable. At the same time, environmental public goods that are 'localized' through access restrictions are often able to deliver benefits to members efficiently. Indeed, there is an extensive body of evidence for the effectiveness of local rules of management for common pool resources that are subject to regulated access (reported in the extensive literature that builds on Ostrom's seminal contribution: Ostrom, 1990).

Taking the services identified in Table 5, the international environmental public goods that are most vulnerable to free-riding behavior and that are most likely to be undersupplied are those for which the supply technology is additive, the cost of provision is high, and large numbers of countries are involved. They include:

1. In situ conservation of endangered species and genetic information.
2. Conservation of harvested wild living resources from ecosystems beyond national jurisdiction.
3. Mitigation of climate change through abatement of $CO_2$ and carbon sequestration.
4. International management of nutrient flows.

For this category of environmental public goods, cooperation and unilateral action is least likely and defection most likely. Indeed, this is reflected in the weakness of the associated MEAs: The Convention on Biological Diversity, the UN Convention on the Law of the Sea and UN Framework Convention on Climate Change. Yet even for this least tractable set of public goods, the fact that some may be jointly produced (reducing the national cost of provision) and that they may yield nationally capturable benefits (increasing the national benefits of provision) increases the payoffs to national action. If complementarity in production and nationally capturable benefits are large enough, the strategic options switch from those associated with the prisoners' dilemma to those associated with the harmony game, where there is no dilemma between individual and collective action.

A second vulnerable category includes international environmental public goods where benefits are limited by the capacity of the least effective country/set of countries, the weakest/weaker link problems. These include:

5. Management of infectious disease
6. Quarantine, port inspections
7. Pest control
8. Eradication of invasive species

Weakest/weaker-link public goods in this category are undersupplied relative to demand by all but one/by most countries. On the positive side there is an incentive to countries with greater capacity to invest in the capacity of the weakest/weaker links in the chain. This is reflected in the major multilateral agreements dealing with these phenomena. For example, both the Sanitary and Phytosanitary Agreement and the International Health Regulations include provisions that direct high-income countries to invest in the capacity of low-income countries to comply with the terms of those agreements. However, where protection against infectious diseases or invasive pests is an impure public good — i.e., where there is a nationally capturable benefit from reducing international risks — individual countries will have an incentive to take unilateral investment in the weakest/weaker links in the chain independent of the Sanitary and Phytosanitary Agreement and the International Health Regulations. The result is a number of bilateral agreements that include capacity building as a specific objective.

A third category of international environmental public goods that is less problematic than it seems at first is that for which the technology of supply involves a weighted sum of national contributions. It includes:

9. Coastal protection against storm damage
10. Flood protection
11. Regulation of air quality, control of $NO_X$ and $SO_2$ emissions
12. Protection of sites of special scientific interest, religious or cultural significance

The weights in each case determine the marginal impact of the contribution of each country. If the weights are different for different countries, then the contributions of those countries are not perfectly substitutable. The impacts of sulfur emissions from different countries, for example, vary with wind patterns, and country's location. The impacts of flood protection vary with local environmental conditions, and so on. Since weighted sum technologies are additive, they are still associated with a strong incentive to free-ride on the efforts of others, but because local conditions matter, they affect the costs and benefits of local provision of the public good, and hence the payoffs to national action. When country-specific net gains from own efforts are high, provision efforts are promoted. The weights in such cases may indicate the degree to which provision of a public good yields nationally capturable benefits — i.e., the degree to which the public good is 'impure'. For example, countries in which a high proportion of emissions to air are deposited on their own soil have a stronger incentive to abate those emissions than countries whose emissions are transported abroad.

The fourth and final category of international environmental public goods described in Table 5 is the least problematic of all. It is the category of best-shot, better-shot and (some) threshold goods public goods. It comprises:

13. Vaccine development
14. Information about disease/pest/invasive risks

While each country would like the others to take on the burden of provision, these public goods will generally be provided by unilateral action. Unilateral action will be taken by the countries that stand to gain the greatest benefits from provision of the public good, and the fact that the remaining countries will free-ride on their efforts has no effect on the level of benefits enjoyed by all.

## DISCUSSION AND CONCLUSIONS

A particular model of collective action, the prisoners' dilemma, is often incorrectly treated as the general model of collective action. In fact a wide range of issues have been analyzed this way without carefully scrutiny to check that their underlying payoff structure corresponds to this particular formalization (Snidal, 1985). There are other models of collective action that have different implications for international cooperation. While provision of some international environmental public goods involves a prisoners' dilemma, provision of others does not. In many cases the incentives to nation states — the payoffs to alternative actions — either supports coordinated action or encourages unilateral action. Understanding when this is the case helps identify where the international community should be focusing its efforts.

For all international environmental public goods, the structure of payoffs to alternative actions reflects a range of environmental, institutional and economic conditions. We have made the point that the public good characteristics of many ecosystem services is socially constructed — open access common pool resources being the classic case. They are non-exclusive by the rules of access that apply, and not by their biophysical characteristics. More generally, governance structures affect the number of parties involved in the provision of public goods, the nature and frequency of interactions between them, the spatial and temporal scale of public good provision, the resources available to change the structure of payoffs, and so on. Changing governance structures changes outcomes by changing payoffs.

What is clear is that we should not expect a positive correlation between the size of the global benefit and the number of parties to an agreement. Inclusiveness is not always beneficial. Kaul *et al.*'s (2003) principle of 'the equivalence of publicness' in the provision of public goods at the international level implies that the set of stakeholders in a transboundary environmental public good should be matched with the set of participants involved in negotiation over its provision. This principle is reflected in the large numbers of signatories to multilateral agreements addressing global public goods. But few such agreements offer significant benefits. It is possible in many cases to achieve better results with a relatively small coalition of states. Free riding is still a risk, but the potential for transfers to induce cooperation between members of the coalition is significantly greater. For example, the Regional Fisheries Management Organizations

(RFMOs) involve smaller numbers of partners and have more precisely defined remits than the UN Convention on the Law of the Sea or the Compliance and Fish Stocks Agreements (Sandler, 2005). They also offer scope for repeated negotiation amongst a relatively small number of parties. They are limited by the fact that they cannot effectively establish exclusive rights for member states, nor do they have the capacity to deal with unregulated fishing by non-members (Barrett, 2004; Munro, 2008), but they do offer the best currently available option for regulating access to sea areas beyond national jurisdiction.

The main conclusion to be drawn from this review is that the ecosystem services that most depend on collective provision are those for which the supply technology is additive, the cost of provision is high, and large numbers of beneficiaries are involved. For these ecosystem services there is little alternative to developing a system of international governance built on multilateral agreement. For all other transboundary ecosystem services, however, there exists at least some incentive for countries to take unilateral action. In some cases, this may involve action to change the payoffs to third parties so as to induce them to provide the public good. In other cases, it may involve direct provision of the public good itself. There are two areas where unilateral action to change the payoffs to third parties has the potential to offer international benefits.

The first is by investing in the capacity of weakest/weaker-link countries in weakest/weaker-link public good supply problems. This is built in to the Sanitary and Phytosanitary Agreement and the International Health Regulations, but there are other examples of weakest/weaker link environmental public goods that have been addressed through international development assistance programs independent of any multilateral agreement. By boosting the capacity of the weakest link in such cases, all other countries benefit.

The second is by investing in the nationally capturable benefits of public good supply so as to change the payoffs sufficiently to induce national action, independent of actions by others. The best current example of this is investment in ecotourism as a way of increasing the nationally capturable benefits of biodiversity conservation. This generates the public good as a by-product of a private good. It recognizes that the incentive to take unilateral action in the provision of any public good is much stronger for 'impure' than for 'pure' public goods. Where there are nationally capturable benefits, then the nation state has an incentive to invest so as to acquire those benefits. Our four examples of this are: coastal protection against storm damage, flood protection, regulation of air quality and control of $NO_X$ and $SO_2$ emissions, and protection of sites of special scientific interest, religious or cultural significance. There are, however, many other ecosystem services that offer benefits at the scale of an individual country in addition to any benefits they offer internationally. In fact the Global Environment Facility exists as a mechanism for exactly this purpose, to change the benefit–cost ratio of national investments that offer a global public benefit. The current scale of GEF operations may be very small relative to the value of the environmental public goods at stake, but it is the right institution to address this category of transboundary ecosystem services.

Finally, there is a class of ecosystem services that falls into the category of best- or better-shot public goods. For this category there are strong incentives to one or more countries to supply them. They include the provision of information on harmful pests or pathogens dispersed via the world system of trade and travel, and the development of vaccines against emerging infectious diseases. We cannot say that the information provided by the Centers for Disease Control is socially efficient from a global perspective, but we can say that it is not significantly different from the social optimum. National expenditures undertaken to protect the national interest offer benefits to people everywhere that are close to being globally efficient.

The better our understanding of the incentives to provide transboundary ecosystem services unilaterally, the better our understanding of the need for collective action where unilateral action is insufficient. Given the lead-time involved in negotiating multilateral environmental agreements, and given the difficulty in negotiating agreements that deliver outcomes significantly different from the non-cooperative outcome, there is a strong case for building the supply of transboundary ecosystem services through unilateral action wherever possible. The existence of global environmental public goods logically requires global environmental governance, but the practicalities of assuring provision of transboundary ecosystem services during a period of rapid environmental change favors unilateral action. Only where unilateral action is unlikely to occur is where it is critical to invest resources in developing a consensus on collective action.

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