

# THE EVOLUTION OF HETEROGENEITY IN BIODIVERSITY AND ENVIRONMENTAL REGIMES

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## ABSTRACT

Biodiversity and environmental protection are examples of international public goods problems that comprise a symmetrical system of rights and obligations. Moreover, the underlying scientific, economic and political conditions do not necessarily lead to a Prisoner's Dilemma. Yet from this symmetrical beginning voluntary (Nash) equilibria often require heterogeneous actions, the resolution of which is often couched as a North-South or East-West issue. We use evolutionary game theory to examine how heterogeneous behavior can emerge over time and find that asymmetries need not be universally determined in terms of economic or technological differences. In particular, we find that the evolution of international environmental protocols is a function of *scale*: the ability to achieve a cooperative solution depends upon the distribution of signatories viz. non-participants in the population at large. Such scale considerations reveal an organizational pattern of collective action that does not require across-the-board contribution or abatement levels.

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## INTRODUCTION

The terms *biodiversity* and *sustainable development* gained worldwide attention in the 1987 UN World Commission on Environment and Development report, *Our Common Future*. The report makes it clear that biodiversity is a public goods problem, whose benefits are largely intangible on an individual scale, but nonetheless essential and, consequently, nonexclusive and nonrivalrous. According to Tuchman Matthews (1991, 31), global environmental trends such as loss of species, ozone depletion and deforestation all pose potentially serious losses to mankind. For example, there have been five major extinctions in the Earth's history and few biologists would disagree that we are at the onset of a sixth (*The Economist* 1999). The difference is that the next appears to have been caused by man's industrial and agricultural encroachment on environmentally critical areas, rather than through a killer asteroid or extreme volcanic conditions. Given the ecological-economic interdependence between humans, wildlife, and habitat resources (John et al. 1994), such a loss in biodiversity is likely to be immiserizing. Yet public action has the potential to reverse the trend. It has been estimated that man must double the amount of land set aside in biodiverse hot spots in order to prevent the loss of 60% of the world's species (animals, plants, and microorganisms) in the next fifty years (CNN broadcast, 1 January 2000).

Biodiversity has recently received a great amount of attention in the literature on international public goods. For example, Sandler (1997, 1998) amalgamates the economic, political and scientific aspects of biodiversity and environmental concerns to create a taxonomy of *Global Challenges* for conflict resolution in the new millennium. In addition, Young (1994, 1998) identifies the separate, but parallel issue that the stages of environmental regime building – agenda formation, negotiation, and operationalization – constitute a sequence of distinct collective action problems. The essays in Kaul et al. (1999) provide a comprehensive survey of international collective action, ranging from intergenerational issues of biodiversity to the environment and cultural heritage.

It is the purpose of this paper to examine the issue of biodiversity regime creation from a game-theoretic perspective. In so doing we concentrate on two issues. The first is the way that contributions are aggregated to create a public good. It is typically assumed that the quantity of the public good is determined by the *sum* of individuals' contributions and that this leads to an N-person version of the Prisoner's Dilemma. The conventional wisdom in international relations is that this results in a no-provision Nash equilibrium unless nations can create reciprocity conditions to constrain their citizens from environmentally harmful behavior.

Yet the Prisoner's Dilemma is not a *fait accompli* because summation is not the only the way in which contributions can be aggregated to create a public good. Indeed, it has been known at least since Hirshleifer's (1983) analysis of weakest link and better shot public goods that the prospects for voluntary contribution are not as dire as the Prisoner's Dilemma predicts. For example, from Young's (1998) perspective on the stages of regime formation, agenda formation is a *weakest link* process – where the level of the public good is determined by the minimal contribution – because often many countries are required in order to achieve a coalition size capable of producing global benefits. In addition to weakest link and best shot we investigate the implications of weaker link and better shot public goods, which are less extreme and more appropriate for biodiversity regime building. In all cases, the underlying game is not the Prisoner's Dilemma.

Hence, the mechanisms for closing the gap between cooperative and noncooperative outcomes are less well known. We provide new examples of such mechanisms.

The second issue we address pertains to the realization that biodiversity is generally either a global or transnational issue. As such, it often involves a heterogeneous population. Indeed, the global diversity of economic development itself is often viewed as a major stumbling block for the formation of regimes. For example, the earth is ill-prepared for over a billion Chinese to operate combustible engine vehicles at a per capita level equivalent to even 1950s America. Yet who is to deny them that right when per capita income reaches the feasible level? We view heterogeneity in the development process as implying asymmetric levels of provision (or abatement) and investigate the ability of international regimes to accommodate differences between North and South or East and West.

Our analysis is based on the evolutionary approach to games of strategy. Beginning with Hirshleifer (1977, 1982) and Axelrod (1984), evolutionary arguments have emerged as a paradigm for the analysis of conflict resolution. This is accomplished via the direct use of Maynard Smith and Price's (1973) biological concept of the evolutionary stable strategy (ESS) to explain how individual agents can close the gap between cooperative and noncooperative outcomes. From a dynamic perspective, the advantage of the evolutionary approach over the classic repeated games approach is that agents are no longer committed to a strategy that most often represents a history-dependent preset program. Instead, agents are involved in a dynamic interplay where they can learn about the relative merits of strategies through a process of trial and error. As a result, cooperation need no longer be achieved through punishment or coercion, but through a process of give and take that more closely resembles the regime building experience (Arce 1999).

Several insights arise from our analysis. First, the majority of the biodiversity games we present are discordant – they possess no pure strategy ESS. This is because any potential regime requires identical agents to behave asymmetrically and it is difficult for regimes to work out who should bear the lion's share of the burden. The need for heterogeneity is rampant, even when the costs and benefits of biodiversity and environmental protection are symmetric. Yet we show that the discord is a function of the evolutionary paradigm itself. This leads us to our second point – biodiversity regimes exhibit the problem of *scale* (Young 1994). To wit, the ability to voluntarily achieve a cooperative solution depends on the size of the population contemplating the regime. When we relax the standard ESS assumption that interaction takes place from a large – for all purposes infinite – population, to one that involves a finite number of actors/states, then cooperation can be achieved. Thirdly, biodiversity can be accomplished through uncorrelated asymmetries. Specifically, it is generally assumed that strategic heterogeneity in environmental regimes is decided by North-South or East-West issues. Our results indicate that abatement and provision asymmetries can be decided by variables other than technological or economic differences.

## THE MODEL

The purpose of this section is to illustrate that the way that conservation and preservation efforts are *aggregated* in order to produce biodiversity and environmental protection is an important strategic consideration for international regime creation. For example, in terms of the basic approach to public goods, it is most often assumed that the level of provision is determined by the

*sum* of agents' contributions. The result is then most often a Prisoner's Dilemma-type situation, which has led to a great deal of emphasis on regime formation when individual action produces a dominant strategy outcome that is universally inefficient (i.e. no provision). Yet this need not be the case. For example, the natural habitat of many species is contiguous, hence, the carrying capacity for species is unlikely to be the sum of the total amount of land set aside, but rather a function of the distribution of the acreage. Examples of *contribution aggregators* that address the question of distribution are weakest link, weaker link, best shot and better shot. We provide examples of these public goods below.

Stemming from the adage that a chain is only as strong as its weakest link, the provision of public goods that embody the *weakest link* is a process by which the lowest contribution determines the entire amount of the public good. A catastrophic example of weakest link biodiversity loss occurred in Venezuela during December 1999, when the forested slopes that previously prevented mud slides were absent. An example of weakest link environmental thinking is then-Chief Economist Lawrence Summer's 1992 infamous World Bank memo on how LDCs are underpolluted, and how increasing their share of dirty industries could be welfare improving on a global scale (*The Economist* 1992). A numerical example of a weakest-link public good is given in Table 1a. As long as contribution  $q_j$  equals zero, the utility,  $U(q_i, q_j)$ , generated is equal to zero regardless of whether  $q_i=0, 1$  or  $2$ . When contributions match at  $q_i=q_j=1$  the utility of the public good increases to 4, and it does not increase again until  $q_i=q_j=2$ . There is nothing player  $i$  can do to increase the level of public good on her own, and if player  $j$  decreases his contribution from a previously reciprocal match, then utility drops as well. As a final example of weakest link, there is the theory that smaller species of animals and plants are the "small parts" of the ecosystem, hence, weeding them out may upset the natural balance and initiate a domino effect (Maruska, 1999).

In *weaker link* public goods the lowest contribution provides the greatest marginal utility. An important aspect of the weaker link is that one player acting alone *can* have some effect on public provision. For example, poor nations lack the economic incentive and funds for habitat preservation, but inaction on the part of central governments need not imply global disaster. Instead, organizations such as Conservation International and the World Wildlife Fund have picked up some of the slack financially, and also educate governments on how market forces can provide incentives to preserve biodiversity (Simpson 1999). We illustrate the weaker link in Table 1b. In contrast to the weakest link,  $q_i=1$  *does* generate public benefit even when  $q_j=0$ . Yet increasing  $q_i$  to 2 when  $q_j=0$  yields a lower marginal utility ( $3.5-3=.5$ ) than compared to a matching increase of  $q_j$  to 1 ( $4-3=1$ ). In an environmental example, movements in marine currents in the North Sea Southern Bight imply that domestic abatement efforts in Belgium and the Netherlands are somewhat productive for cleaning up their coastlines, but are even more so if they are matched by efforts in France (Tulkens 1979).

Our motivation for this section began with the idea that the larger the stretch of contiguous land or ocean protected for species development, the larger the carrying capacity. This is an example of *best shot*. Another example is that as conservation shifts from individual and groups of species to entire ecosystems, monitoring technologies become key issues. Best shot applies because the contributor with the most sophisticated technology identifies a regime's monitoring capacity. An example is lidar observations of stratospheric aerosol composition. Our best-shot example is

given in Table 1c. As player i's contribution is always at least that of player j's, it is player i who uniquely determines the utility generated from voluntary contributions.

The final contribution aggregator we consider is *better shot*, where the highest contribution generates the greatest marginal utility. In contrast to best shot, it is now possible for the smaller contribution,  $q_j$ , to increase utility, although never at a rate greater than the larger contribution,  $q_i$ . This can be shown by analyzing the case where  $q_i=1$  and  $q_j=0$  in Table 1d. If  $q_j$  is raised to 1 the marginal utility is 1 (5-4). Yet if  $q_j$  remains at zero and  $q_i$  increases from 1 to 2 this has a marginal utility of 3 (7-4). The supplement of contiguous set-asides for species development with zoos, compounds and sanctuaries is a better-shot technology. Another example is the information produced by multinational chemical companies' mass screening programs (bioprospecting) in rainforests. An environmental example of best shot is CO<sub>2</sub> monitoring. The station atop Mauna Loa provides the best current atmospheric data, but Antarctic ice core samples supplement this data from an alternative latitude and are also a better historical data source.

### Game Theoretic Structure

The nature of interdependence in public good provision varies with each of the contribution aggregators outlined above. Each agent also has a marginal cost of provision, which is independent of the contribution aggregator. In order to address the issue of voluntary provision, we will assume that a player's payoff,  $V_i(q_i, q_j)$ , is determined by the formula:

$$V_i(q_i, q_j) = U(q_i, q_j) - 2 \cdot q_i, \quad (1)$$

where:  $U(q_i, q_j)$  is the utility generated by all voluntary contributions, as determined by the contribution aggregator, and coefficient 2 on  $q_i$  is agent i's marginal cost of provision. We will assume constant and identical marginal cost throughout.

The games given in Figures 1a-d correspond to the contribution aggregators in Tables 1a-d, respectively, where player 1 is row and player 2 is column. The games are derived by applying Eq.(1) to each strategy pair in the respective table. For example, in the weakest link when  $q_1=2$  and  $q_2=1$  in Table 1a indicates that  $U(2,1)=4$ . The payoffs for strategy pair  $q_1=2$  and  $q_2=1$  in Figure 1a are then  $V_1(2,1) = 4 - 2 \cdot 2 = 0$  and  $V_2(2,1) = 4 - 2 \cdot 1 = 2$ , as given by the formula in Eq.(1). In the same way,  $q_1=0$  and  $q_2=2$  yield  $U(2,0)=0$  from Table 1a. Hence, in Figure 1a this strategy pair generates the payoff  $V_1(0,2) = 0 - 2 \cdot 0 = 0$  for player 1, and  $V_2(0,2) = 0 - 2 \cdot 2 = -4$  for player 2.

These games constitute the basis for our analysis, which will be numerical as there is very little to be gained in terms of functional forms. Additionally, the games are voluntary contribution games, hence, there is complete information about preferences as we are not addressing the separate issue of preference revelation for public goods.

The games themselves are symmetric, but this is by design for several reasons. First, as Sand (1991, 244) argues, the public nature of global environmental problems implies a symmetrical system of reciprocal rights and obligations. Second, Sandler (1997, 162) observes the growing trend that emissions protocols are no longer characterized by across-the-board cutbacks among signatories, but rather tailored reductions that effectively equate the marginal cost of emissions reductions.

Third, the evolutionary paradigm implies that we will *not* interpret any of these games as 2-player games. Instead, over time a population of agents plays the game, with the payoffs representing the outcome from each random pairwise matching of agents. The evolutionary analysis of games is necessarily symmetric; strategies represent phenotypes/genotypes, and payoffs the fitness of strategies. A game is *symmetric* if for any two strategies  $q$  and  $q^m$  it is the case that  $V_1(q, q^m) = V_2(q^m, q)$ . Each payoff is then an equivalent measure of the fitness of strategy  $q$  when confronted with a mutant  $q^m$ . For this reason we can drop the player subscript on payoffs,  $V$ , when we conduct our evolutionary analysis in the following section.

## THE EVOLUTIONARY PARADIGM

The biodiversity issue is one that will never be fully put to rest. Transnational and global partners will continually face environmental challenges, hence, a static interpretation of the games presented above is inadequate. Instead, we must focus on the way that institutions are created through repeated interaction among the participants and allow for the possibilities of learning and imitation. Beginning with Hirshleifer (1977, 1982), strategic issues pertaining to collective action have been couched within the evolutionary paradigm. More specifically, the use of Maynard Smith and Price's (1973) biological concept of the evolutionary stable strategy (ESS) has been used as a static framework for characterizing the outcomes that are a result of dynamic interaction among a population of boundedly rational actors. This interpretation is justified on the basis that the ESS represents a reduced form of two possible dynamic processes within a population of agents: replicator dynamics and learning/imitation.

*Replicator dynamics* refer to the way in which a strategy should grow within a population of alternative strategies, based on a Darwinian notion of natural selection. Strategies that generate high relative payoffs will tend to thrive while those that generate low payoffs will die out. In essence, there is a large population in which each individual is hardwired (genetically endowed) with one of the strategies, and then individuals/strategies are randomly matched in a series of pairwise encounters in which the stage game is played. Replicator dynamics then specify that a strategy's genetic fitness is a function of the payoff that it generates in pairwise matchings. Furthermore, the growth rate of the strategy is a function of its average relative fitness within the population of strategies at that point in time.

Economics, being a social science that is based on a theory of higher order rationality of humans, has altered the strategically hardwired genotypes of biology in order to allow for an agent to learn the relative merits of a strategy, and imitate those strategies that generate greater relative payoffs. In this way an individual that is initially endowed with an inferior strategy is not predestined to extinction. The underlying dynamic process becomes one where the probability that an individual switches to another strategy is based on that individual's own experience in pairwise matchings, and her limited observations of others' experiences. This process of learning and imitation then converges to a version of the replicator dynamics, as Börgers and Sarin (1997) and Schlag (1998), among others, have shown.

Surprisingly, both of these dynamic concepts can be characterized in terms of Maynard Smith and Price's (1973) evolutionary stable strategy. This is due to Taylor and Jonker's (1978) result that the conditions (2)-(3) below are a static characterization of replicator dynamics.

*Definition:* For any 2-player symmetric game the strategy  $q$  is an *evolutionary stable strategy* (ESS) if, for any other strategy  $q^m \neq q$ , the following conditions hold (Maynard Smith and Price 1973):

$$V(q,q) \geq V(q^m,q), \text{ and} \quad (2)$$

$$\text{if } V(q,q) = V(q^m,q) \text{ then } V(q,q^m) > V(q^m,q^m) \quad (3)$$

A strategy,  $q$ , is stable for the population if it allows the population to thrive and fend off all competitor mutations within the population. This means that the fitness generated from a pairwise matching of population strategies,  $V(q,q)$ , should exceed that of a pairwise matching of a mutant,  $q^m$ , with the population strategy,  $V(q^m,q)$ . This is condition (2), which also specifies that an ESS is a symmetric Nash equilibrium. In order to ensure dynamic stability, if the measures of fitness  $V(q,q)$  and  $V(q^m,q)$  are equal, then the mutant cannot survive and thrive within the population. This requires that the population strategy's fitness is greater when matched with the mutant,  $V(q,q^m)$ , than is the mutant's when matched with itself,  $V(q^m,q^m)$ . It is expressed mathematically by Eq.(3). Together, (2) and (3) imply that that we can focus on the main diagonal of the games under analysis. Otherwise, the ESS would not truly represent a characteristic of the population as a whole:

*Whether or not off-diagonal solutions are efficient, these solutions are not available as evolutionary equilibria in a homogeneous population! The reason why is that they require complementary pairing of strategy choices, which is not possible in random encounters within a homogenous population, Hirshleifer (1982,15).*

Certainly, the asymmetry of roles can be achieved through a symmetric mixed strategy, but we will rule out mixtures because they are weak in the sense that all pure strategies with positive measure also generate the same expected payoff. As a consequence, this is unpalatable from a political perspective because mixed strategies are unstable with respect to slight deviations from others (Ward 1996). Moreover, Maynard Smith (1988, 251) argues that from an evolutionary perspective independent randomization is likely to be rare in a behavioral context with finite populations (e.g. one with political representative as actors). This is because randomization is not achieved with an internal device, but with reference to an external event (e.g. a coin toss), and the population must have a means for selecting among an infinite variety of such devices that can generate the same expected payoffs. Finally, randomization can be inefficient, as it is in the case of 'Chicken.'

## **Evolutionary equilibria**

We are interested in the ESS of our games because they encapsulate a situation where agents interact repeatedly and can learn from their experiences in order to create regimes that capture the benefits of biodiversity. Both Ward (1996) and Sandler (1997) advocate the evolutionary approach because agents are allowed to learn mutually beneficial strategies and abandon suboptimal ones. We begin, however, with a pessimistic result on the evolution of environmental regimes through voluntary contribution:

*Result 1:* the biodiversity games are discordant (Arce 1999). That is, no evolutionary equilibria exist for weaker link, better shot, nor best shot. Additionally, ESS does not refine away the inefficient symmetric Nash equilibria in weakest link.

*Proof:* Referring to Figure 1a, the pure strategy Nash equilibria for the weakest link are the strategy pairs  $(q_1, q_2) = (0,0), (1,1),$  and  $(2,2)$ . Each of these satisfies Eq.(2), hence, all are ESS. In Figure 1b the weaker link Nash equilibria are  $(0,1)$  and  $(1,0)$ . Neither of these is symmetric, therefore, they cannot be ESS. The Nash equilibria for best shot (Figure 1c) are the asymmetric strategy pairs  $(0,2)$  and  $(2,0)$ . Again, these are not symmetric so  $ESS = \emptyset$  for best shot. In Figure 1d the Nash equilibria are again asymmetric:  $(1,2)$  and  $(2,1)$ .

Biologically speaking, ruling out individual randomization (mixtures) to overcome the nonexistence result implies that our population cannot be monomorphic. An evolutionary stable population is *monomorphic* if individuals' behavior varies from strategy to strategy over time, as would be the case if players employed individual mixed strategies (Maynard Smith and Price 1973). A polymorphic population, however, is still possible. An ESS is *polymorphic* if strategies of individuals are fixed, with different individual types distributed across the strategy space. The distinction is between heterogeneity at the population level (polymorphism) and individual level (monomorphism). The evolution of population heterogeneity in terms of polymorphic regimes – where the behavior of signatories need not be uniform – is the subject of the next section.

## THE SCALE OF THE PROBLEM

A question that is well-known in the natural sciences is whether observations and tendencies gathered from the analysis of a local or isolated ecosystem can be readily extended to make global or system-wide conclusions and vice-versa? This is the problem of *scale* (Levin 1992). For example, Benedict (1991, 115) points out that ozone time series data must be properly disaggregated in order to account for various scales of variation: short-term (weather related), seasonal (solar induced) and long-term (climate-policy related). The use of genetically engineered organisms for agricultural use is also a question of scale. For example, in the Fall of 1999 Monsanto faced widespread public and legal fears that the potential ecological impact of its Roundup Ready seeds would be substantially different from results generated in the laboratory (Huber 1999). Similarly, concerns about the extent of desertification brought on by repeated drought conditions in the Sahelian region of Africa during the late 1960s and early 1970s have failed to be justified on a global scale (Forse 1989).

Young (1994) recognizes that the problem of scale may exist for collective action. For example, there may be significant differences in the way that neighbors can resolve the common pool resource problems (at the micro level) and what can be done at the macro level in terms of international regimes. From an evolutionary perspective this difference exists as well. Consider, for example, Axelrod's (1984) Prisoner's Dilemma tournament and Güth's (1995) work on reciprocity in bilateral bargaining situations. Each of these is concerned about the evolution of preferences at the micro scale. To wit, can a system of anonymous cooperation or reciprocity persist in a society given that there may be behavioral, mental and/or economic costs associated with the population's maintenance of such as system? When viewed as human traits, such

preferences compete with other types of mutant behavior (e.g. greediness), and an evolutionary scale is justified. Yet from the perspective of international regime building there is less anonymity, greater discretionary control over when and how participants face the public goods issues underlying biodiversity, and greater cultural and economic differences among the participants. It is instead a macro level scale. Moreover, it is unconvincing to expect that mutant or rogue behavior is unlikely to be relegated to an infinitesimal level from within the international community. This is because there are little or no property rights produced in international biodiversity and environmental regimes, and punishing deviants may be too costly for those who choose to continue according to the norms specified by the regime (Barrett 1994).

Young's question can then be viewed as the following: can what we learn from collective action games meant to model the development of human preferences at a micro scale be transferred to a set of propositions for international collective action at the macro scale? Alternatively, is the pessimism generated by the nonexistence established by Result 1 at the micro scale well-founded for international regimes? Hirshleifer (1983, 155-6) indirectly sheds some light on the issue through the implicit argument that as the size ( $N$ ) of the population changes, the subsequent distribution of the population is key for determining the effectiveness of group provision. From an evolutionary perspective, consider the (2,2) ESS for the weakest link. If  $N$  is now increased and a significant proportion of the new agents are  $q^m=0$  mutants, is (2,2) an ESS? The point is mute from the perspective of preference formation because the probabilities that (i) the population strategy  $q=2$  meets with a  $q^m=0$  mutant, and (ii) two  $q^m=0$  mutants encounter each other, are infinitesimal and are therefore treated as *identical*. We will formalize this below. Yet from an international perspective the size of  $N$  and the distribution of strategies across  $N$  may matter a great deal. For example, not all signatories to the Kyoto Protocol are required to take specific actions. Indeed, the only countries that are required to abate under Kyoto are the so-called Annex I signatories (OECD, former Soviet Union and East European transition economies). Hence, there is a *persistent* mutant population or inactive signatories which contributors must be stable against.

### Addressing Scale in an Evolutionary Context

The point of the previous subsection is to argue that the evolutionary analysis of biodiversity regimes may be dependent on the scale of the analysis. There are two scales to consider. One is that of preference formation over time – Axelrod's (1984) and Guth's (1995) experiments are examples – where the long-run probabilities that a mutant encounters another mutant, or a member of the population encounters a mutant, are considered to be so remote that both are treated to be identically infinitesimal. An equivalent definition of ESS more clearly illustrates this point:

*Definition:* The strategy,  $q$ , is an evolutionary stable strategy (ESS) if, for any other strategy  $q^m \neq q$ , the following condition holds for sufficiently small  $\varepsilon > 0$ :

$$\underbrace{(1-\varepsilon) \cdot V(q, q) + \varepsilon V(q, q^m)}_{\text{Expected payoff of } q} > \underbrace{(1-\varepsilon) \cdot V(q^m, q) + \varepsilon \cdot V(q^m, q^m)}_{\text{Expected payoff of } q^m}. \quad (4)$$

When there is a continuum of players,  $\varepsilon$  is properly interpreted as the proportion of the population with mutant strategy  $q^m$ . Then, the evolutionary value of a population-mutant encounter,  $V(q, q^m)$ ,

on the left-hand side of (4), and that of a mutant-mutant encounter,  $V(q^m, q^m)$ , on the right-hand side are both given the infinitesimal weight of  $\epsilon$  when calculating the expected fitness of  $q$  versus  $q^m$ .

What we argue is that the international scale is different from the preference formation scale and this has to be accounted for when analyzing international regimes. As Young (1994, 433) makes clear, the evolution of preferences takes place in an environment where entitlements of ownership are present; these have little or no immediate counterparts in a society of sovereign states. Instead, phenomena such as the global climate system, the ozone layer, sea levels, etc., encompass resources with respect to groups of states that share jurisdiction rather than entitlements of ownership. Moreover, even when jurisdiction is granted there may exist rogue nations (e.g. whaling). In this way scale itself is often endogenous and may be simultaneously determined within the institutional design of biodiversity regimes (Snidal 1994). In essence, the evolution of individual preferences is an ultra-long-run phenomenon. International biodiversity regimes have yet to achieve this scale. The actions of each individual need to be accounted for in order to gauge the potential for a regime's success. In particular, mutant behavior in the form of nonparticipation may be persistent, or the protocol itself may call for abatement by only a subgroup of signatories.

In a finite population the predominant strategy (the ESS) and the mutant strategy do not confront the same population profile when they are pairwise matched with another random strategy. As Schaffer (1988) points out, if the population is not infinite, then the  $\epsilon$  on the left-hand side of Eq.(4) – used to calculate the expected payoff of  $q$  – is not the same as the  $\epsilon$  used to calculate the expected payoff of  $q^m$  on the right-hand side of Eq.(4). In this case, Schaffer posits the following condition:

*Definition:* for a finite population of size  $N$ , the strategy  $q$  is a finite and locally evolutionary stable strategy,  $ESS_N$ , if, for a mutant strategy  $q^m$  and single type of mutant population of size  $M$ , the following inequality holds:

$$\underbrace{\left[1 - \frac{M}{N-1}\right] \cdot V(q, q) + \frac{M}{N-1} \cdot V(q, q^m)}_{\text{Finite expected payoff of } q} > \underbrace{\left[1 - \frac{M-1}{N-1}\right] \cdot V(q^m, q) + \frac{M-1}{N-1} V(q^m, q^m)}_{\text{Finite expected payoff of } q^m} \text{ for } N-1 > M > 0. \quad (5)$$

On the left-hand side the coefficient on  $V(q, q)$  is the probability that  $ESS_N$  strategy  $q$  is matched with another  $q$  when there are  $M$  mutants in the population. The coefficient on  $V(q, q^m)$  is the probability that  $q$  is matched with a mutant  $q^m$ . On the right-hand side the coefficient on  $V(q^m, q)$  is the probability that a mutant  $q^m$  is randomly matched with the  $ESS_N$  strategy  $q$ , and the coefficient on  $V(q^m, q^m)$  is the probability that it is instead matched with a mutant other than itself. Persistent mutant behavior is recognized, as the ratio  $\frac{M}{N-1}$  is not assumed to be infinitesimal. Consequently, the probability that a  $q$ -strategist encounters a  $q^m$ -strategist,  $\frac{M}{N-1}$ , is different from that of one  $q^m$ -strategist encountering another,  $\frac{M-1}{N-1}$ .

Equation (5) makes it immediately clear that we can use  $ESS_N$  as a formalization of Snidal's (1994) claim that the scale of participation is endogenously determined. The potential number of actors/states is  $N$ , with  $M$  nonparticipating agents and  $N-M$  agents left to sustain the biodiversity regime in the face of such non-participation or signatory inaction. Specifically, when  $N$  is finite and  $M$ , the number of mutants, is not inconsequential, the effect is to add *strategic heterogeneity*.

For example, from the Southern perspective, climate change and development are to be linked. The North should bear the brunt of the costs so that controlling emerging nations' behavior does not interfere with development, both on equity grounds and because of the North's historical responsibility for the decline in biodiversity (Ward 1996, 853).  $ESS_N$  allows for biodiversity regimes that reflect this type of behavior by endogenizing it as a form of strategic heterogeneity. For the games under analysis this implies a polymorphic population where a player is identified as a strategy, rather than as a row or column player. This enables us to avoid the discord associated with result 1 because population behavior is no longer required to be uniform! Moreover  $ESS_N$  represents an alternative to the standard method of generating polymorphisms via a population frequency interpretation of mixed strategies (e.g. Cornell and Roll 1981). The condition given in Eq.(3) has the effect of making an ESS mixture stable with respect to deviations by others. The analog in  $ESS_N$  is that heterogenous/polymorphic behavior will be stable with respect to a *range* of participants.

If we multiply through by  $N-1 > 0$  the following useful characterization of  $ESS_N$  arises:

$$V(q,q) > V(q^m,q) - \underbrace{\frac{M-1}{N-M-1} \cdot [V(q,q^m) - V(q^m,q^m)]}_{\substack{q \text{ is a better reply to } q^m \\ \text{than } q^m \text{ is to itself}}} - \underbrace{\frac{1}{N-M-1} \cdot [V(q,q^m) - V(q^m,q)]}_{\text{measure of spitefulness}}. \quad (6)$$

This representation illustrates several important characteristics of  $ESS_N$ . To begin, it is clear that  $q$  need not be a symmetric Nash equilibrium. Indeed, the mutant strategy may be a strict better response to  $q$  than  $q$  is to itself, i.e.  $V(q^m,q) > V(q,q)$ . For the infinite version of ESS given in Eqs.(2)-(3) the equality  $V(q^m,q) = V(q,q)$  was allowed so long as  $q$  was strictly a better response to the mutant  $q^m$  than  $q^m$  was to itself. This condition is extended in the second term on the right-hand side of Eq.(6). We must now consider how  $q$  performs when matched against a subpopulation of size  $M$  of  $q^m$ 's in addition to the traditional consideration of the performance of a mutant  $q^m$  in a population of  $q$ 's. In particular, the second term on the right-hand side tells us that as long as mutant behavior is not so rare as to rule out pairwise matchings among mutants ( $M \geq 2$ ), then in small populations the survival of a non-Nash  $ESS_N$  is dependant on its ability to make hay against mutants.

In addition,  $ESS_N$  illustrates the evolutionary concern with *relative* payoffs, as opposed to *absolute* payoffs in Nash equilibria. The third term on the right-hand side of Eq.(6) is Schaffer's (1989, 30) specification of a *spiteful strategy*. The  $ESS_N$   $q$  is spiteful if it causes a decrease in its own fitness that is less than the decrease it causes in the fitness of the mutant population. It is harmful to itself but more so to the mutant. Consequently, mutant behavior *benefits* the population profile in relative terms. Spitefulness is a distinctive feature of ESS in finite populations.

## Scale Matters

We are now ready to test whether our ESS results for biodiversity games are sensitive to scale. Specifically, can regime formation take place when the mutant/inactive population is likely to persist? Our first consideration is the weakest link, which possesses ESS's along the main diagonal of (0,0), (1,1), and (2,2). Achieving efficiency through the (2,2) outcome is a classic coordination problem in the sense of Schelling (1960). Again, Hirshleifer's (1983) intuition on the effects of scale is twofold. If the number of players increases, but heterogeneity does not, then efficiency is maintained. If heterogeneity is present, then efficiency is difficult to maintain. The result below formalizes this intuition.

*Result 2:* Scale affects the weakest link game in the following way (proofs in appendix):

- (i) ESS (0,0) is not  $ESS_N$  for  $M \geq 2$ .
- (ii) ESS (1,1) is not  $ESS_N$  for  $M \geq 2$ .
- (iii) ESS (2,2) is not ESS for  $M > 0$ .

This result states that strategic heterogeneity is destabilizing for the weakest link. For example, with respect to the (2,2) outcome when smaller contributors are not inconsequential this pushes the weakest link away from efficiency. The result is a coordination failure. The players cannot coordinate on  $q=2$  because there is always a subset of players with  $q^m < 2$  and this destabilizes the system. Furthermore, the weakest link technology itself does not allow  $q=2$  to be spiteful or for even  $q=2$  to be a better reply than  $q^m < 2$  is to itself because the diagonal entries are Nash equilibria. Similar reasoning holds for  $q=1$  and  $q=0$ . As a consequence, scale is of the utmost consideration in such an environment. In other words, biodiversity regimes that embody the weakest link require unanimity, otherwise, they are doomed to failure.

The analysis of scale is specifically designed to identify organizational patterns of large ensembles of smaller units (Levin 1992). In terms of the games under study, this implies that we are looking for patterns of collective action as identified by  $ESS_N$ . For example, Schaffer (1989, 43) points out the following subtlety of  $ESS_N$ : finite populations with many  $ESS_N$  players may not persist whereas finite populations with a few  $ESS_N$  players might. The following sequence of results provide examples of this heretofore theoretical possibility, and additional patterns of scale pertaining to the organization of behavior in international collective action.

*Result 3:* For the weaker link game:

- (i) (1,1) is an  $ESS_N$  for  $2M-3 > N-1 > M > 3$ .
- (ii) (2,2) is never an  $ESS_N$ .

*Result 4:* Outcome (2,2) is an  $ESS_N$  for the best shot game if  $7M - 4 > N-1 > M > 3$ .

*Result 5:* Efficient outcome (2,2) is an  $ESS_N$  for better shot when  $5M - 8 > N-1 > M > 3$ .

Results 3-5 identify organizational patterns of heterogeneous provision across the population of nations/states. These in turn are key to the development of principles for the management of international collective action. In all cases an upper bound is put on the number of players who

provide at the  $ESS_N$  level ( $q=1$  for weaker link and  $q=2$  for best and better shot). The pattern of collective action is such that equilibrium not only depends on mutual reinforcement, but also through an  $ESS_N$ 's performance as a better reply to mutant strategies – Shaffer's (1988) subtlety of  $ESS_N$ .

Result 3 identifies that under the weaker link there is more potential for subgroups to provide in the presence of inactive signatories as compared to the weakest link. For example, if  $M=7$  then there can be 2 or 3 members of the population who set  $q=1$ . Furthermore, in this example the  $ESS_N$  players constitute less than half the size of the population. This scale phenomenon is not identifiable via ESS because none of the diagonal elements of Table 1b are Nash, hence, they cannot be ESS. Yet result 3 illustrates that an  $ESS_N$  can exist for a game where the ESS set was empty! Furthermore, this  $ESS_N = (1,1)$  – is not even a symmetric Nash equilibrium for the game. This is due to the reliance of the  $q=1$  strategy on its performance against mutant strategies; it is not a best reply to itself, but it is the best reply to a  $q^m=0$  or a  $q^m=2$  mutant. Hence, the presence of one such type of mutant enables  $q=1$  to persist. Finally, in terms of the entire population, Result 3 establishes a polymorphism that is stable for a *range* of  $ESS_N$  agents.

In terms of the management of international collective action, the  $ESS_N q=1$  constitutes a voluntary level of contribution that is intermediate as compared to  $q=0$  or  $q=2$ . There is a great deal of benefit to intermediate behavior. As Arce (1999) has shown, if a pattern arises where some agents unilaterally provide an intermediate level of a public good, and match even larger contributions – i.e. they *lead by example* – then efficiency can subsequently be achieved without the need for coercion or punishment. We have shown that the initial stage of intermediate provision can indeed be generated as part of an organizational pattern that produces this equilibrium process. It is a scale phenomenon. An example is the US and Canada's ban on aerosol CFCs in the 1970s prior to the Montreal Protocol.

We now turn to the case of best shot (Result 4). The efficiency of the best shot is enhanced to the degree that it results in a distribution with players who prefer a higher level of provision, i.e. through the actions of a subgroup that provides  $q=2$ . For matches within the  $q=2$  subgroup the outcome is (2,2), which is suboptimal. However, the best response of mutants is  $q^m=0$ , implying that  $(q^m, q)$  and  $(q, q^m)$  matchings result in efficient provision. In essence, we have found an incentive for 'good citizenship' on the part of a minority of states in order to overcome the nonexistence of a symmetric solution. The need for good citizenship within the organizational pattern of provision is another example of scale.

Our final test of scale is with respect to the better shot (Result 5). Once again, the symmetry requirement leads to  $ESS = \emptyset$ , but the problem is not as endemic as it is in the best shot. This is because the Nash equilibria are (1,2) and (2,1). Each agent is bearing some of the costs of provision. In this case the overriding theme for resolving nonexistence and increasing efficiency is the performance of  $q=2$  as a best reply to  $q^m=0$  or  $q^m=1$ . The  $ESS_N$  is not a best reply to itself, but instead depends upon its performance against mutants to persist. Consequently, this allows for a subset of the population to play  $ESS_N$  strategy  $q=2$ .

## POLICY IMPLICATIONS

Results 2-5 demonstrate that scale matters in collective action. Accounting for scale leaves us with several policy considerations. First, what we learn about the equilibria that emerge from the evolutionary analysis on a preference or local scale – where long-term interaction is formally a continuum – does not readily transfer to finite and discrete interaction on the international scale. For example, under  $ESS_N$  the nonexistence of a pure strategy equilibrium is no longer the problem that it is for ESS. In a biodiversity context this translates into regimes that allow for signatory heterogeneity, rather than imposing universal contribution or abatement levels.

Our analysis has been entirely based on symmetric games that are meant to encompass the symmetrical system of rights and obligations that characterize the public nature of environmental problems. The problem we have illustrated is that from this symmetrical beginning there is often a need for asymmetrical regimes that differentiate treaty obligations according to the special circumstances of each party. The strategic heterogeneity implied by Results 3-5 has real world counterparts. The European Community's 1988 Directive on the Limitation of Certain Pollutants into the Air from Large Combustion Plants (88/609/EEC) is such an example. Sand (1991, 245) reports that the directive is a strategically heterogeneous one that even allowed for temporary increased emissions in Greece, Ireland and Portugal. Other UN Trust Funds that call for heterogeneous contributions are the Mediterranean Convention, the Endangered Species Convention and the Transboundary Air Pollution Convention. Chander et al. (1999) argue that the Kyoto Protocol on  $CO_2$  should be viewed as a worldwide protocol, rather than an Annex I protocol. Although  $CO_2$  emissions are commonly associated with the summation aggregator, they can as well be thought of as better shot because abatement is also a technological issue. Hence, in Result 5 the Annex I countries are assigned the  $ESS_N$  of  $q=2$  as in Kyoto.

Most often this differentiation takes place on the basis of technological and economic differences (e.g. the UN's global assessment scale), as was the case for Kyoto. We argue, however, that strategic heterogeneity need not be determined on economic or development grounds alone. There is unexplored potential for determining environmental providers – even leaders – on the basis of *uncorrelated asymmetries* – perceivable differences among members of a population that can be used as conventions to assign roles. The uncorrelated asymmetry becomes of interest because Results 3-5 identify a range of players who can play a pure strategy  $ESS_N$ . This range property distinguished the  $ESS_N$  polymorphism from the mixed strategy polymorphism of ESS. In a mixed strategy every payoff that is played with positive probability must generate the same expected payoff. In contrast, the pure strategy polymorphism of  $ESS_N$  are not required to produce acts that are payoff equivalent *if* they are generated by uncorrelated asymmetries (Maynard Smith 1984, 96). A biological example is the resident of a territory versus a seemingly symmetric intruder. Occupation is a factor that is determined independently of strategy, but may serve as a cue as to who is willing to escalate in a contest. A socioeconomic example is, “first come, first served.” The seniority system in the US Congress is a political one (Cornell and Roll 1981).

In terms of international environmental regimes, continental unity is an example of an uncorrelated asymmetry. Again, the US and Canada's pre-Montreal ban on CFC aerosol comes to mind. Another example is the leadership exemplified by Visigoth countries' actions in arctic waters versus the dilatory behavior of their Soviet and US counterparts. Only through such heterogeneity

did the Arctic Environmental Protection Strategy (AEPS) evolve. The presence of grass roots movements domestically may prove to be an uncorrelated asymmetry. Further research is required on the use of such asymmetries to promote biodiversity and environmental regimes.

### APPENDIX: PROOFS OF RESULTS 2-5

We begin by imposing the *population restriction*  $N-M-1 > 0$ . This implies that a pairwise matching between players of  $ESS_N$  strategy  $q$  is possible. Then, multiplying Eq.(6) through by  $[N-M-1]>0$  yields Eq.(7), which will use in our proofs.

$$[N-M-1] \cdot \{V(q,q) - V(q^m,q)\} + V(q,q^m) > [M-1] \cdot \{V(q^m,q^m) - V(q,q^m)\} + V(q^m,q) \quad (7)$$

**Result 2:** If we let  $q=2$  and  $q^m=1$ , then Eq.(7) becomes:

$$[N-M-1] \cdot \{V(2,2) - V(1,2)\} - V(1,2) > [M-1] \cdot \{V(1,1) - V(2,1)\} - V(2,1)$$

$$[N-M-1] \cdot \{4-2\} + 0 > [M-1] \cdot \{2-0\} + 2 \Rightarrow N > 2M+1$$

Hence,  $q=2$  is *not* ESS if  $2M+1 \geq N$ . By definition, the population size must be such that  $N > M+1$ .

Combining these two inequalities yields  $2M+1 > M+1 \Rightarrow M > 0$ . The proofs for (0,0) and (1,1) directly follow from this technique.

**Result 3:** for  $q=1$  and  $q^m=0$  Eq.(7) becomes

$$[N-M-1] \cdot \{V(1,1) - V(0,1)\} + V(1,0) > [M-1] \cdot \{V(0,0) - V(1,0)\} + V(0,1)$$

$$[N-M-1] \cdot \{2-3\} + 1 > [M-1] \cdot \{0-1\} + 3 \Rightarrow [N-M-1] - 1 < [M-1] - 3 \Rightarrow N < 2M-2$$

For the case of  $q^m=2$  Eq.(7) becomes

$$[N-M-1] \cdot \{V(1,1) - V(2,1)\} + V(1,2) > [M-1] \cdot \{V(2,2) - V(1,2)\} + V(2,1)$$

$$[N-M-1] \cdot \{2-2.5\} + 4.5 > [M-1] \cdot \{4-4.5\} + 2.5 \Rightarrow [N-M-1] < [M-1] + 4 \Rightarrow N < 2M+4$$

The first restriction,  $N < 2M-2$  is the biting constraint. This, combined with the population constraint  $N-1 > M$  implies  $2M-3 > N-1 > M \Rightarrow M > 3$ .

For  $q=2$  and  $q^m=1$  Eq.(7) becomes:

$$[N-M-1] \cdot \{V(2,2) - V(1,2)\} + V(2,1) > [M-1] \cdot \{V(1,1) - V(2,1)\} + V(1,2)$$

$$[N-M-1] \cdot \{4-4.5\} + 2.5 > [M-1] \cdot \{2-2.5\} + 4.5 \Rightarrow [N-M-1] < [M-1] - 4 \Rightarrow N < 2M-4$$

For  $q=2$  and  $q^m=0$  Eq.(7) becomes:

$$[N-M-1] \cdot \{V(2,2) - V(0,2)\} + V(2,0) > [M-1] \cdot \{V(0,0) - V(2,0)\} + V(0,2)$$

$$[N-M-1] \cdot \{4-3.5\} - 5 > [M-1] \cdot \{0+.5\} + 3.5 \Rightarrow [N-M-1] > [M-1] + 8 \Rightarrow N > 2M+8$$

Together, these conditions imply  $2M-4 > 2M+8 \Rightarrow -4 > 8$ , which cannot hold.

**Result 4:** For  $q=1$  and  $q^m=2$  Eq.(7) becomes:

$$[N-M-1] \cdot \{V(1,1) - V(2,1)\} + V(1,2) > [M-1] \cdot \{V(2,2) - V(1,2)\} + V(2,1)$$

$$[N-M-1] \cdot \{2-3\} + 5 > [M-1] \cdot \{3-5\} + 3 \Rightarrow [N-M-1] < 2 \cdot [M-1] + 2 \Rightarrow N < 3M+1$$

For  $q=1$  and  $q^m=0$  Eq.(7) becomes:

$$[N-M-1] \cdot \{V(1,1) - V(0,1)\} + V(1,0) > [M-1] \cdot \{V(0,0) - V(1,0)\} + V(0,1)$$

$$[N-M-1] \cdot \{2-4\} + 2 > [M-1] \cdot \{0-2\} + 4 \Rightarrow [N-M-1] < [M-1] - 1 \Rightarrow N < 2M-1$$

Clearly, the restriction arising from  $q^m=0$  is the one that bites. This, along with the population restriction implies  $2M-1 > M+1 \Rightarrow M > 2$ .

For  $q=2$  and  $q^m=1$  Eq.(7) becomes

$$[N-M-1] \cdot \{V(2,2) - V(1,2)\} + V(2,1) > [M-1] \cdot \{V(1,1) - V(2,1)\} + V(1,2)$$

$$[N-M-1] \cdot \{3-5\} + 3 > [M-1] \cdot \{2-3\} + 5 \Rightarrow [N-M-1] < .5[M-1] + 1 \Rightarrow N < 1.5(M+1)$$

This combined with population restriction  $N > M+1$  will not bite. We then turn to  $q=2$  and  $q^m=0$ , from which Eq.(7) yields:  $[N-M-1] \cdot \{V(2,2)-V(0,2)\} + V(2,0) > [M-1] \cdot \{V(0,0)-V(2,0)\} + V(0,2)$ .

$$[N-M-1] \cdot \{3-7\} + 3 > [M-1] \cdot \{0-3\} + 7 \Rightarrow -4N+4M+4 > -3M+3+4 \Rightarrow 7M-3 > 4M \Rightarrow 7M-3 > 4M+4 \Rightarrow M > 2.33 \Rightarrow M > 3.$$

**Result 5:** For  $q=2$  and  $q^m=0$  Eq.(7) becomes:

$$[N-M-1] \cdot \{V(2,2)-V(0,2)\} - V(0,2) > [M-1] \cdot \{V(0,0)-V(2,0)\} - V(2,0)$$

$$[N-M-1] \cdot \{7.5-7\} + 3 > [M-1] \cdot \{0-3\} + 7 \Rightarrow [N-M-1] > -6[M-1] + 8 \Rightarrow N > -5M+15$$

For  $q=2$  and  $q^m=1$  Eq.(7) becomes:

$$[N-M-1] \cdot \{V(2,2)-V(1,2)\} - V(1,2) > [M-1] \cdot \{V(1,1)-V(2,1)\} - V(2,1)$$

$$[N-M-1] \cdot \{7.5-8\} + 6 > [M-1] \cdot \{4-6\} + 8 \Rightarrow [N-M-1] < 4 \cdot [M-1] - 4 \Rightarrow N < 5M-7$$

These constraints can be jointly satisfied when  $5M-7 > -5M+15 \Rightarrow M > 2.2 \Rightarrow M \geq 3$ , at which point  $5M-7 > N > M+1$  (the population constraint) is met as well.

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**Table 1a: Weakest-Link**

$U(q_i, q_j)$	$q_i$	$q_j$
0	0	0
0	1	0
4	1	1
0	2	0
4	2	1
8	2	2

**Table 1b: Weaker-Link**

$U(q_i, q_j)$	$q_i$	$q_j$
0	0	0
3	1	0
4	1	1
3.5	2	0
6.5	2	1
8	2	2

**Table 1c: Best-Shot**

$U(q_i, q_j)$	$q_i$	$q_j$
0	0	0
4	1	0
4	1	1
7	2	0
7	2	1
7	2	2

**Table 1d: Better-Shot**

$U(q_i, q_j)$	$q_i$	$q_j$
0	0	0
4	1	0
5	1	1
7	2	0
10	2	1
11.5	2	2

**Figure 1a: Weakest-Link Game**  
 $[MC_1=MC_2=2]$

$\downarrow q_1/q_2 \rightarrow$	0	1	2
0	0, 0	0, -2	0, -4
1	-2, 0	2, 2	2, 0
2	-4, 0	0, 2	4, 4

**Figure 1b: Weaker-Link Game**  
 $[MC_1=MC_2=2]$

$\downarrow q_1/q_2 \rightarrow$	0	1	2
0	0, 0	3, 1	3.5, -.5
1	1, 3	2, 2	4.5, 2.5
2	-.5, 3.5	2.5, 4.5	4, 4

**Figure 1c: Best-Shot Game**  
 $[MC_1=MC_2=2]$

$\downarrow q_1/q_2 \rightarrow$	0	1	2
0	0, 0	4, 2	7, 3
1	2, 4	2, 2	5, 3
2	3, 7	3, 5	3, 3

**Figure 1d: Better-Shot Game**  
 $[MC_1=MC_2=2]$

$\downarrow q_1/q_2 \rightarrow$	0	1	2
0	0, 0	4, 2	7, 3
1	2, 4	4, 4	8, 6
2	3, 7	6, 8	7.5, 7.5