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# COPING WITH TRAGEDIES OF THE COMMONS

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## ABSTRACT

Contemporary policy analysis of the governance of common-pool resources is based on three core assumptions: (*a*) resource users are norm-free maximizers of immediate gains, who will not cooperate to overcome the commons dilemmas they face; (*b*) designing rules to change incentives of participants is a relatively simple analytical task; and (*c*) organization itself requires central direction. The chapter shows that these assumptions are a poor foundation for policy analysis. Findings from carefully controlled laboratory experiments that challenge the first assumption are summarized. A different assumption that humans are fallible, boundedly rational, and norm-using is adopted. The complexity of using rules as tools to change the structure of commons dilemmas is then discussed, drawing on extensive research on rules in field settings. Viewing all policies as experiments with a probability of failure, recent research on a different form of general organization—that of complex adaptive systems—is applied to the process of changing rules. The last sections examine the capabilities and limits of a series of completely independent resource governance systems and the importance of encouraging the evolution of polycentric governance systems.

## THE POLICY PUZZLE

Since the influential article by Hardin (1968), "the tragedy of the commons" has been used as a metaphor for the problems of overuse and degradation of natural resources including the destruction of fisheries, the overharvesting of timber, and the degradation of water resources. Many policy analysts, scholars, and public officials agree with Hardin's conclusion that the participants in

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a commons dilemma are trapped in an inexorable process from which they cannot extract themselves. External authorities are presumably needed to impose rules and regulations on local users, since they will not do this themselves. Viewing resource users as trapped in a tragedy of their own making is consistent with contemporary textbooks on resource economics and the predictions derived from noncooperative game theory for finitely repeated dilemmas (E Ostrom et al 1994).

Further, the way that "scientific management of natural resources" is taught to future regulators of natural resources keeps fisheries, forests, and water resources as relatively homogeneous units that are closely interrelated across a vast domain. Irrigation systems are interlinked along watersheds of major river systems. Fish and wildlife species tend to migrate over a large range. This approach, as it has been applied to fisheries management, is described by Acheson et al (1998:391–92).

> For those trained in scientific management, it is also an anathema to manage a species over only part of its range. From the view of fisheries scientists and administrators, it is not rational to protect a species in one zone only to have it migrate into another area where it can be taken by other people due to a difference in regulations. As a result, the units to be managed range along hundreds of miles of coast and can only be managed by central governments with jurisdiction over the entire area. Lobsters, for example, extend from Newfoundland to the Carolinas; swordfish migrate from the Caribbean to Newfoundland and Iceland. From the point of view of the National Marine Fisheries Service, it makes sense to have a set of uniform regulations for the entire US coast rather than one for each state. (See Sherman & Laughlin 1992)

Contemporary policy analysts also share a belief in the feasibility of designing optimal rules to govern and manage common-pool resources for a large domain utilizing top-down direction. Because common-pool resources are viewed as relatively homogeneous and interlinked, and because simple models exist of how they work, officials acting in the public interest are considered capable of devising uniform and effective rules for an entire region. What is needed is to gather reliable, statistical information on key variables, determine what the optimal harvesting pattern should be, divide the harvesting level into quotas, and assign quotas to users. Prescriptions calling for central governments to impose uniform regulations over most natural resources are thus consistent with important bodies of theoretical work, as well as the most advanced scientific approaches to resource policy.

These prescriptions are not, however, supported by empirical research. Field studies in all parts of the world have found that local groups of resource users, sometimes by themselves and sometimes with the assistance of external authorities, have created a wide diversity of institutional arrangements for coping with common-pool resources (McCay & Acheson 1987, Fortmann & Bruce 1988, Berkes 1989, V Ostrom et al 1993, Netting 1993, Bromley et al 1992, Tang 1992, Blomquist 1992). Examples also exist of commons dilemmas that have continued unabated. One conclusion that can firmly be made in light of extensive empirical evidence is, however, that overuse and destruction of common-pool resources is not a determinant and inescapable outcome when multiple users face a commons dilemma. Scholars have begun to identify the conditions of a resource, and of the users of a resource, that are most conducive to local users self-organizing to find solutions to commons dilemmas (see E Ostrom 1992, 1998b; Baland & Platteau 1996). Further, the broad design principles that characterize robust self-organized resource governance systems have been identified (E Ostrom 1990) and found basically sound by other scholars (Morrow & Hull 1996).

Another important set of findings is that national governmental agencies are frequently unsuccessful in their efforts to design effective and uniform sets of rules to regulate important common-pool resources across a broad domain. Many developing countries nationalized all land and water resources during the 1950s and 1960s. The institutional arrangements that local users had devised to limit entry and use lost their legal standing, but the national governments lacked funds and personnel to monitor these resources effectively. Thus, common-pool resources were converted to a de jure government-property regime but reverted to a de facto open-access regime (Arnold 1998, Arnold & Stewart 1991). The incentives of a typical commons dilemma were accentuated because local users were implicitly told that they would not receive the benefits of adopting a long-term view in their use of the resource. When resources that were previously controlled by local participants have been nationalized, state control has usually proved to be less effective and efficient than control by those directly affected, if not disastrous in its consequences (Curtis 1991, Panayotou & Ashton 1992, Ascher 1995). The harmful effects of nationalizing forests that had earlier been governed by local user-groups have been well documented for Thailand (Feeny 1988), Africa (Shepherd 1992, Thomson 1977, Thomson et al 1992), Nepal (Arnold & Campbell 1986), and India (Gadgil & Iyer 1989; Jodha 1990, 1996). Similar results have occurred in regard to inshore fisheries taken over by state or national agencies from local control by the inshore fishermen themselves (Cordell & McKean 1992, Cruz 1986, Dasgupta 1982, Higgs 1996, Pinkerton 1989).

Tang (1992) and Lam (1998) have also both found that large-scale government irrigation systems do not tend to perform at the same level as smaller-scale, farmer-managed systems (see also Mehra 1981, Levine 1980, Bromley 1982, Hilton 1992). In a study of over 100 irrigation systems in Nepal, Lam (1998) finds that the cropping intensity and agricultural yield of crudely constructed irrigation systems using mud, rock, timbers, and sticks is significantly higher than the performance of systems built with modern concrete and iron headworks operated by national agencies.

A considerable disjunction exists between currently accepted policy recommendations, based on well-received theories of human behavior in commons dilemmas, and evidence from the field (Berkes et al 1989). These findings challenge three of the most important theoretical foundations of contemporary policy analysis. One foundation is the model of the human actor that is used. Resource users are explicitly thought of as norm-free maximizers of immediate gains, who will not cooperate to overcome the perverse incentives of dilemma situations in order to increase their own and others' long-term benefits unless coerced by external authorities. Government officials are implicitly depicted, on the other hand, as seeking the more general public interest and being able to analyze long-term patterns in order to design optimal policies.

A second foundational belief is that designing rules to change the incentives of participants is a relatively simple analytical task best done by objective analysts not intimately related to any specific resource. Analysts view most resources in a particular sector as relatively similar and sufficiently interrelated that they need to be governed by the same set of rules. Third is the view that organization itself requires central direction. Consequently, the multitude of self-organized resource governance systems are viewed as mere collections of individual agents out to maximize their own short-term returns. The groups who have actually organized themselves are invisible to those who cannot imagine organization without rules and regulations issued by a central authority (see, for example, Lansing 1991, Lansing & Kremer 1994).

I propose to show that these three assumptions are a poor foundation for public policy recommendations. To do this, I first need to define what is meant by a common-pool resource, which is done in the next section. I then use the Institutional Analysis and Development (IAD) framework to show how the seven components of an action situation can be used to construct an appropriation dilemma—the central common-pool resource problem identified in most policy texts. To address the adequacy of the model of the human actor used, I summarize the findings from a series of carefully controlled laboratory experiments of appropriation dilemmas. Given that predictions based on the model of a norm-free, myopic, and maximizing individual are not supported, I then present a closely related but alternative conception of human behavior—applicable to resource users and government officials alike. Humans are viewed as fallible, boundedly rational, and norm-using. In complex settings, no one is able to do a complete analysis before actions are taken, but individuals learn from mistakes and are able to craft tools—including rules—to improve the structure of the repetitive situations they face.

I go on to explore the complexity of using rules as tools to change the structure of commons dilemmas. First I describe the seven clusters of rules that affect the components of any action situation, and then describe the specific rules that are used in field settings by resource users and government agencies. An examination of the types of rules used in the field yields several important findings. First, the number of rules actually used in field settings is far greater than generally recognized. Second, the type of rules is different. Some rules recommended in the policy literature are not found among the rules used by self-organized systems.

Given the complexity of the process of designing rules to regulate the use of common-pool resources, I argue that all policy proposals must be considered as experiments. No one can possibly know whether a proposed change in rules is among the more optimal rule changes or even whether a rule change will lead to an improvement. All policy experiments have a positive probability of failing. I draw on recent research by Holland (1995) and colleagues at the Sante Fe Institute to discuss the attributes and mechanisms of a different form of general organization—a complex adaptive system—that is not the result of central direction. Complex adaptive systems cannot be understood if one tries to fit these systems into the image of an organization with a central director.

I show how the parallel efforts by a large number of local resource users to search out and design local rule configurations may find better rule combinations over the long term, whereas top-down design processes are more limited in their capacities to search and to find appropriate rules. All forms of decision making have limits. I discuss the limits of a series of completely independent resource governance systems and the importance of building polycentric governance systems with considerable overlap to combine the strengths of parallel search and design processes with the strengths of larger systems in conflict resolution, acquisition of scientific knowledge, monitoring the performance of local systems, and the regulation of common-pool resources that are more global in their scope. The resulting polycentric governance systems are not directed by a single center. They, too, are complex adaptive systems, requiring policy analysts to change their fundamental views of organization in order to cope more effectively with tragedies of the commons and many of the other problems facing modern societies.

## THE COMPONENTS OF A COMMONS PROBLEM

### *The Definition of a Common-Pool Resource*

A common-pool resource, such as a lake or ocean, an irrigation system, a fishing ground, a forest, or the atmosphere, is a natural or man-made resource from which it is difficult to exclude or limit users once the resource is provided, and one person's consumption of resource units makes those units unavailable to others (E Ostrom et al 1994). Thus, the trees or fish harvested by one user are not available for others. The difficulty of excluding beneficiaries is a characteristic that is shared with public goods, and the subtractability of the resource units is shared with private goods. The focus in this chapter is primarily on renewable natural resources as exemplars of common-pool resources, but the theoretical arguments are relevant to man-made common-pool resources.

When the resource units produced by a common-pool resource have a high value and institutional constraints do not restrict the way resource units are appropriated, individuals face strong incentives to appropriate more and more resource units, leading to congestion, overuse, and even the destruction of the resource itself. Because of the difficulty of excluding beneficiaries, the free-rider problem is a potential threat to efforts to reduce appropriation and improve the long-term outcomes achieved from the use of the common-pool resources. When free riding is a major problem, those who would willingly reduce their own appropriations if others did are unwilling to make a sacrifice for the benefit of a large number of free riders.

Consequently, one important problem facing the joint users of a common-pool resource is known as the appropriation problem, given the potential incentives in all jointly used common-pool resources for individuals to appropriate more resource units when acting independently than they would if they could find some way of coordinating their appropriation activities. Joint users of a common-pool resource often face many other problems, including assignment problems, technological externality problems, provision problems, and maintenance problems (E Ostrom et al 1994, E Ostrom & Walker 1997). And the specific character of each of these problems differs substantially from one resource to the next. In this chapter, I focus more on appropriation problems, since they are what most policy analysts associate with “the tragedy of the commons.”

### *A Baseline Appropriation Situation*

No single model adequately captures the essential structure of all common-pool resources. There are instead universal components of all situations in which individuals interact on a structured and repetitive basis. These components take multiple values and combine to produce an incredible variety of action situations. The structure of any action situation can be analyzed by identifying seven components and how they generate a set of incentives for those involved. The components include (*a*) participants, (*b*) positions, (*c*) actions, (*d*) outcomes, (*e*) transformation functions linking actions and outcomes, (*f*) information, and (*g*) payoffs (including both positive returns and negative sanctions where relevant). Basically, one is interested in learning about the number and characteristics of participants in positions where they must choose among diverse actions in light of the information they possess about how actions are linked to potential outcomes and about the costs and benefits assigned to actions and outcomes (see E Ostrom et al 1994:ch. 2). Although it is possible to identify the component parts, the resulting action situation is a complex system whose structure is derived from the combination of parts. Appropriation situations have many structures, depending on the combination of particular attributes of each of these seven components.

In order to understand the process of coping with appropriation problems, we need to start with a static, baseline situation that is as simple as we can specify without losing crucial aspects of the problems that real appropriators face in the field. Further, we need to start with an "institution-free" baseline situation so that we can understand the outcomes predicted and achieved in such a baseline situation and the processes involved in changing the structure by changing rules that affect it. I outline the baseline appropriation situation that is based on accepted theory and has been used in a large number of laboratory experiments (see E Ostrom et al 1992, 1994). This institution-free, static, baseline situation has the following characteristics:

1. It involves a set of *n* symmetric appropriators who are interested in withdrawing resource units from a common-pool resource over a finite time horizon.
2. No differentiation exists in the positions these appropriators hold relevant to the common-pool resource. In other words, there is only one position of appropriator.
3. Appropriators must decide how to allocate their time and effort in each time period. One can think of these appropriators as being "endowed" with a set of assets, *e*, that they allocate each time period to two activities. Each day, for example, appropriators must decide whether to spend time trying to harvest resource units from the common-pool resource or to use time in their next best opportunity, such as working in a local factory. To simplify the problem, we posit that all appropriators have the same endowment, face the same labor market, and can earn a fixed wage for any time they allocate to working for a factory.
4. The actions affect the amount of resource units that are appropriated from the common-pool resource or wages earned in the labor market.
5. Transformation functions map the actions of all appropriators, given the biophysical structure of the resource itself, onto outcomes. Although these functions are frequently stochastic in field settings and are affected by many variables in addition to the actions of individuals, here I consider only determinant functions of appropriation actions in the baseline setting. The wage function simply multiplies the amount of time allocated to it by what-

ever is the standard wage. The appropriation function is a concave function, $F$, that depends on the number of assets, $x_i$, allocated to appropriation from the common-pool resource. Initially, the sum of individuals' actions, $\Sigma x_i$, generates better outcomes than a safe investment in wage labor. If the appropriators decide to allocate a sufficiently large number of their available assets, the outcome they receive is less than their best alternative. In other words, allocating too many assets to the common-pool resource is counterproductive. Such a function is specified in many resource-economics textbooks based on the pathbreaking articles by Gordon (1954) and Scott (1955).

6. As an initial information condition, we assume that appropriators know the shape of the transformation function and know that they are symmetric in assets and opportunities. Information about outcomes is generated after each decision round is completed.

7. Payoff rules specify the value of the wage rate and the value of the resource units obtained from the common-pool resource. Specifically, the payoff to an appropriator is given by

$$we \qquad \text{if } x_i = 0 \text{, or}$$

$$w(e - x_i) + (x_i / \Sigma x_i)\, F(\Sigma x_i) \qquad \text{if } x_i > 0.$$

If appropriators put all of the assets into wage labor, they receive a certain return equal to the amount of their endowment times the wage rate. If appropriators put some of their endowed assets into wage labor and some into the common-pool resource, they get part of their return from wages and the rest from their proportional investment in the common-pool resources times the total output of the common-pool resource as determined by function $F$.

## *Assumptions about Actors*

To explain and predict the outcome of any situation, one needs to specify four key characteristics of the actors who are participating in the situation: (*a*) the type of preferences held, (*b*) how information is processed, (*c*) the formula or heuristic used for making decisions, and (*d*) the resources brought to the situation. The theory of complete rationality uses the assumptions that (*a*) individuals have a complete and transitive ordering of preferences over all outcomes that is monotonically related only to their own objective payoffs, (*b*) all relevant information generated by the situation is used in making decisions, (*c*) actors maximize their own expected payoffs, and (*d*) all needed resources to act in this situation are possessed.

The theory of norm-free, complete rationality has proved to be extremely useful in a diversity of circumstances where the institutional arrangements reduce the number of options and complexity of the situation and reward those who maximize expected returns to self while punishing those who do not. When such situations are completely specified, clear predictions of equilibrium outcomes are derived. Behavior in experimental laboratories and in the field closely approximates the predicted equilibrium in simple action situations where selection pressures retain those who maximize their own expected returns and thin out those who do not.

The theory of norm-free, complete rationality is also useful in a variety of other situations to enable the analyst to undertake a full analysis and predict equilibrium outcomes. If behavior deviates from the predicted outcomes, one has a clear benchmark for knowing how far behavior deviates from that predicted by this theory. Below, therefore, I initially use the theory of norm-free, complete rationality and the theory of finitely repeated games to predict what the outcome would be if a set of experimental subjects were to face a fully specified baseline appropriation situation as outlined above. I then modify this set of assumptions in light of the evidence obtained in the experimental laboratory (and supplemented by field studies).

### *Predicted Outcomes for a Common-Pool Resource in the Laboratory*

Laboratory experiments provide an opportunity to observe how humans behave in situations that are simple compared with field settings but nonetheless characterize essential common elements of relevant field situations. In the laboratory experiments conducted at Indiana University, we thought it crucial to examine behavior in an appropriation situation with a nonlinear transformation function and a sufficient number of players so that knowledge of outcomes did not automatically provide information about each player's actions. In this chapter, I can only briefly discuss the results of these experiments. All procedures and specifications are thoroughly documented in E Ostrom et al (1994) and in journal articles cited therein. In the baseline experiments, we utilized the following equation for the transformation function, $F$:

$$23\,(\Sigma x_i) - 25\,(\Sigma x_i)^2$$

Eight experienced subjects participated in all experiments discussed in this chapter. Each subject was assigned either 10 tokens, in the low-endowment condition, or 25 tokens, in the high-endowment condition, in each round of play. Their outside opportunity was valued at $0.05 per token. They earned $0.01 on each outcome unit they received from investing tokens in the common-pool resource. Subjects were informed that they would participate in an experiment that would last no more than two hours. The number of rounds in each experiment varied between 20 and 30. Instead of asking subjects to pretend they were fishing or harvesting timber, we described the situation as involving a choice between investing in either of two markets having the structure specified above. In addition to being told the payoff function specifically, subjects were provided with look-up tables that eased their task of estimating outcomes.

With these specifications, the predicted symmetric equilibrium strategy for a finitely repeated game in which subjects do not discount the future is for each subject to invest 8 tokens in the common-pool resource, for a total of 64 tokens. The prediction is the same for both endowment levels. At this level of investment, each subject would earn \$0.66 per round in the 10-token experiments and \$0.70 per round in the 25-token experiments (players were paid half of their computer returns in the 25-token experiments to keep the payoffs roughly similar). The players could, however, earn considerably more if the total number of tokens invested in the common-pool resource was 36, rather than 64. This optimal level of investment would earn each subject \$0.91 per round in the 10-token experiment and \$0.83 per round in the 25-token experiment. The baseline experiment is an example of a commons dilemma in which the predicted outcome involves substantial overuse of a common-pool resource. A much better outcome could be reached if subjects were to lower their joint use.

## BEHAVIOR IN A SPARSE EXPERIMENTAL *N*-PERSON, REPEATED APPROPRIATION DILEMMA

As predicted, subjects interacting in baseline experiments substantially overinvested (documented in E Ostrom et al 1994). Subjects in the 10-token experiments achieved, on average, 37% of the maximum available to them and subjects in the 25-token experiments received –3% (E Ostrom et al 1994:116). At the individual level, however, subjects rarely invested 8 tokens, which is the predicted level of investment at equilibrium. Instead, all experiments provided evidence of an unpredicted and strong pulsing pattern in which individuals appear to use a simple heuristic. They increase their investments in the common-pool resource until there is a strong reduction in yield, at which time they tend to reduce their investments. As the yield again goes up, they repeat the cycle. At an aggregate level, behavior approximates the predicted Nash equilibrium in the 10-token experiment but is much lower than predicted in the 25-token experiment. No game-theoretic explanation exists for the pulsing pattern or the substantial difference between the 10-token and the 25-token experiments.

These laboratory experiments have been replicated by other researchers (Rocco & Warglein 1995) with similar results. An extremely interesting study was recently completed (Deadman 1997) in which artificial agents were programmed to use a variety of heuristics similar to those used by the human subjects in these experiments and to interact in a simulated environment that exactly replicated the baseline experiments. Deadman found that the specific results obtained in any series of runs depended on the particular heuristic (or mix of heuristics) programmed. Artificial agents did consistently produce the same kind of pulsing returns, and the consistent difference between 10-token and 25-token environments was also observed. Deadman (1997:175–76) described his results as follows:

> As in CPR [common-pool resource] experiments, the group performance for the simulation follows an oscillating pattern in which high performance leads to over investment in the CPR and the resultant drop in performance causes a reduction in group-wide investment in the CPR.... Still more interesting is the observation that the simulations perform similarly to subjects in laboratory experiments in terms of average performance over time. At the ten token endowment, the simulations perform near the Nash equilibria over time. At the 25 token endowment, the simulations perform near zero percent of optimum over time.

Consequently, both human subjects and artificial agents programmed to use heuristics performed similarly in the baseline environment.

## STRUCTURAL CHANGE IN THE LABORATORY

In addition to the baseline experiments, we have explored how rule changes affect outcomes. Rule changes were operationalized in the set of instructions given to subjects and in the procedures adopted within the experiment. The first structural change was an information rule change. Instead of forbidding all communication among subjects, as in the baseline experiments, subjects were now authorized to communicate with one another in a group setting before returning to their terminals to make their own private decisions. This introduction of an opportunity for “cheap talk,” where agreements are not enforced by an external authority, is viewed as irrelevant within the context of a noncooperative game with a Pareto deficient equilibrium.[1] The same outcome is predicted as in the baseline experiment. In a second series of experiments, we changed the authority and payoff rules to allow subjects to sanction one another at a cost to themselves. Because using this option produces a benefit for all at a cost to the individual, the game-theoretic prediction for a finitely repeated game is that no one will choose the costly sanctioning option. In a third series, we changed the authority rule to allow subjects to covenant with one another to determine their investment levels and to adopt a sanctioning system if they wished. Again, the predicted outcome is the same. In all three of these structurally changed appropriation experiments, however, subjects demon-

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[1] In coordination games, on the other hand, cheap talk helps players agree on which equilibrium to select among several. In coordination games, individuals have an incentive to keep a promise of a future action that leads both players to a better equilibrium. In a social-dilemma game, each player has an incentive to use cheap talk to deceive the other player into switching strategies so that the first player can reap a much higher payoff. It is for this reason that cheap talk is considered irrelevant in dilemma games but useful in coordination games (see Farrell & Rabin 1966).

strated their willingness and ability to search out and adopt better outcomes than those predicted.

## *Face-to-Face Communication*

In the repeated communication experiments, subjects made 10 rounds of decisions in the context of the baseline appropriation game. At this point, subjects listened to an announcement that told them they would have an open group discussion before each of the continuing rounds of the experiment. The subjects left their terminals and sat in a group facing one another. After each discussion, they returned to their terminals and entered anonymous decisions. Subjects used face-to-face communication to discuss what strategy would gain them the best outcomes and to agree on what everyone should invest in the subsequent rounds. After each decision round, as in the baseline experiments, they learned what their aggregate investments had been, but they did not learn the decisions of individual players. Thus, they learned whether total investments were greater than their agreement. Although in many rounds, subjects did exactly as they had promised one another, some defections did occur. If promises were not kept, subjects used this information to castigate the unknown promise breaker.

This opportunity for repeated face-to-face communication was extremely successful in increasing joint returns in the 10-token experiments, where subjects obtained close to 100% of the maximum available returns. There were only 19 instances out of 368 total opportunities in which a subject invested more in the common-pool resource than agreed upon—a 5% defection rate (E Ostrom et al 1994:154). In the 25-token experiments, subjects also improved their overall performance, but the temptation to defect was greater. Subjects in the 25-token baseline experiments had received total returns that were slightly below zero, while in the communication experiments, they obtained on average 62% of the maximum available returns (with considerable variance across experiments). The defection rate was 13% percent. Our conclusion in completing an analysis of these experiments was as follows:

> Communication discussions went well beyond discovering what investments would generate maximum yields. A striking aspect of the discussion rounds was how rapidly subjects, who had not had an opportunity to establish a well-defined community with strong internal norms, were able to devise their own agreements and verbal punishments for those who broke those agreements.... In many cases, statements like "some scumbucket is investing more than we agreed upon" were a sufficient reproach to change defectors' behavior. (E Ostrom et al 1994:160)

That subjects had internalized norms regarding the importance of keeping promises is evidenced by several of their behaviors. First, simply promising to cut back on their investments in the common-pool resource led most subjects to change their investment pattern. Second, subjects were indignant about evidence of investment levels higher than that promised and expressed their anger openly. Third, those who broke their promise tended to revert to the promised level after hearing the verbal tongue-lashing of their colleagues. These findings are consistent with a large number of studies by other researchers (Sally 1995).

## *Sanctioning Experiments*

Participants in field settings are usually able to communicate with one another on a face-to-face basis, at least from time to time, either in formally constituted meetings or at social gatherings. In most field settings, however, participants have also devised a variety of formal or informal ways of sanctioning one another if rules are broken. Engaging in costly monitoring and sanctioning behavior is, however, not consistent with the theory of norm-free, complete rationality (Elster 1989:40–41). Thus, it is important to ascertain whether subjects in a controlled setting would actually pay in order to assess a financial punishment on the behavior of other participants. The short answer to this question is yes.

All sanctioning experiments used the 25-token design because defections were much higher in this design. Subjects played 10 rounds of the baseline game, modified so that the individual as well as total contributions were reported. Subjects were then told that in the subsequent rounds they would have an opportunity to pay a fee in order to impose a fine on the payoffs received by another player. The fees ranged in diverse experiments from \$0.05 to \$0.20 and the fines from \$0.10 to \$0.80. In brief, the finding from this series of experiments is that much more sanctioning occurs than the predicted zero level. Subjects reacted both to the cost of sanctioning and to the fee-to-fine relationships. They sanctioned more when the cost of sanctioning was less and when the ratio of the fine to the fee was higher. Sanctioning was primarily directed at those who invested more in the common-pool resource, but some sanctioning appeared to be directed by those who had been fined in a form of "blind revenge" against those whose investments were lower than others and were thus suspected of having sanctioned them. In this set of experiments, subjects were able to increase their returns modestly to 39% of maximum, but when the costs of fees and fines were subtracted from the total, these gains were wiped out. When subjects were given a single opportunity to communicate prior to the implementation of sanctioning capabilities, they were able to gain an average of 85% of the maximum payoffs (69% when the costs of the fees and fines were subtracted).

## *Covenanting Experiments*

In self-organized field settings, participants rarely impose sanctions on one another that have been devised exogenously, as the experimenters did in the above sanctioning experiments. Sanctions are much more likely to emerge from an endogenous process of crafting their own rules, including the punishments that should be imposed if these rules are broken. Spending time and effort designing rules creates a public good for all involved and is thus a second-level dilemma no more likely to be solved than the original dilemma. This is the foundation for the repeated recommendation that rules must be imposed by external authorities who are also responsible for monitoring and enforcing these rules.

Subjects experienced with baseline and sanctioning experiments were recalled and given an opportunity to have a "constitutional convention" in the laboratory to decide whether or not they would like to have access to a sanctioning mechanism like the one described above, how much the fines and fees should be, and what joint investment strategy they would like to adopt. All of these groups were endowed with 25 tokens in each round. Four out of six experimental groups adopted a covenant in which they specified the number of tokens they would invest and the level of fines to be imposed. The fines determined by the participants ranged from \$0.10 to \$1.00. The groups that crafted their own agreements were able to achieve an average of 93% of the maximum available returns in the periods after their agreement, and the defection rate for these experiments was only 4%. The two groups that did not agree to their own covenant did not fare as well. They averaged 56% of the maximum and faced a defection rate of 42%. In other words, those subjects who used an opportunity to covenant with one another to agree on a joint strategy and choose their own level of fines received very close to optimal results, based entirely on their own promises and their own willingness to monitor and sanction one another when necessary (see Frohlich et al 1987 for similar findings).

## WHAT THEORY OF HUMAN BEHAVIOR IS CONSISTENT WITH EVIDENCE FROM LABORATORY EXPERIMENTS?

The appropriation experiments briefly summarized above provide the following picture of behavior in $N$-person commons-dilemma situations:[2]

1. When individuals are held apart and unable to communicate face to face (or via the type of signalling that is feasible in two-person situations), they overuse a common-pool resource.
2. Individuals use heuristics in dealing with complex problems.
3. Heuristics vary in their capabilities to cope with a changing configuration of actions by other participants.

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[2] This picture is also consistent with the experimental results obtained by Abbink et al 1996, Andreoni 1989, Frey & Bohnet 1996, Frohlich & Oppenheimer 1970, Güth et al 1982, Hackett et al 1994, Hoffman et al 1996, Isaac & Walker 1988, and Orbell & Dawes 1991.

4. Individuals initially use an opportunity for face-to-face discussions to share their understanding of how their actions affect the joint outcomes and arrive at a common understanding of the best joint strategy available to them.
5. Individuals are willing to promise others, whom they assess as being trustworthy, that they will adopt a joint plan of action. Most individuals keep their promises (in situations where substantial advantage can accrue for breaking the promise).
6. If agreements are broken, individuals become indignant and use verbal chastisements when available. They are also willing to use costly sanctions, and even tend to overuse them, but they do not use grim trigger strategies.
7. When given an opportunity to craft their own rules and sanction nonconformance to these rules, many groups are willing to do so. Through their own efforts, these groups achieve close to optimal results. Those who forego such an opportunity are not able to sustain a high level of performance.

In other words, individuals initially rely on a battery of heuristics in response to complexity. Without communication and agreements on joint strategies, these heuristics lead to overuse. On the other hand, individuals are willing to discuss ways to increase their own and others' payoffs over a sequence of rounds. Many are willing to make contingent promises when others are assessed as trustworthy. A substantial number of individuals, but not all, are trustworthy and reciprocate the trust that has been mutually extended. When behavior not consistent with reciprocity is discovered, individuals are willing to use retribution in a variety of forms but not the form used to predict the possibility of optimal outcomes when these situations are modeled as indefinitely repeated games.

The assumption that individuals are able to engage in problem solving to increase long-term payoffs, to make promises, to build reputations for trustworthiness, to reciprocate trustworthiness with trust, and to punish those who are not trustworthy, leads to a different type of policy analysis than the assumption that individuals seek their own short-term, narrow interests even when presented with situations where everyone's joint returns could be substantially increased. Using the latter theory leads to the policy advice that rules to reduce overuse must be devised by external authorities and enforceably imposed on local users. This has been the foundation for most policy prescriptions regarding the regulation of common-pool resources during the second half of the twentieth century.

A better foundation for public policy is to assume that humans may not be able to analyze all situations fully but that they will make an effort to solve complex problems through the design of regularized procedures and will be able to draw on inherited capabilities to learn norms of behavior, particularly reciprocity (E Ostrom 1998a, Bendor 1987). Such a behavioral theory of boundedly rational and norm-using behavior views all policies as experiments and asks what processes of search and problem solving are more likely to arrive at better experiments. The key problems to be solved are how to ensure that those using a common-pool resource share a similar and relatively accurate view of the problems they need to solve, how to devise rules to which most can contingently agree (Levi 1988), and how to monitor activities sufficiently so that those who break agreements (through error or succumbing to the continued temptations that exist in all such situations) are sanctioned, ensuring that trust and reciprocity are supported rather than undermined (Bendor & Mookherjee 1990).

The dilemma never fully disappears, even in the best operating systems. Once an agreement has been reached, however, appropriators are no longer making their decisions in a totally independent manner that is almost guaranteed to lead to overuse. But the temptation to cheat always exists. No amount of monitoring and sanctioning reduces the temptation to zero. Instead of thinking of overcoming or conquering tragedies of the commons, effective governance systems cope better than others with the ongoing need to encourage high levels of trust while also monitoring actions and sanctioning rule infractions.

Presenting this difference in a theoretical perspective based on carefully designed laboratory experiments is the first task that I set out to accomplish. Boundedly rational, local users are potentially capable of changing their own rules, enforcing the rules they agree upon, and learning from experience to design better rules. The next task is to show why multiple, boundedly rational, local users are better at designing rules than a single team of boundedly rational officials in a central agency. To do this, I draw on research about the type of rules used in the field.

## EXPERIMENTING WITH RULES IN THE FIELD

With this change in perspective, we can think of appropriators trying to understand the biophysical structure of a common-pool resource and how to affect each other's incentives so as to increase the probability of sustainable and more efficient use over the long term. Instead of being given a set of instructions with the transformation function fully specified, they have to explore and discover the biophysical structure of a particular resource that will differ on key parameters from similar resources in the same region. Further, appropriators have to cope with considerable uncertainty related to the weather, complicated growth patterns of biological systems that may at times be chaotic in nature, and external price fluctuations affecting the costs of inputs and value of outcomes (see Wilson et al 1991, 1994). In addition to the physical changes that they can make in the resource, they can use tools to change the structure of the action situations they face. These tools consist of seven clusters of rules that directly affect the components of their own action situations:

1. Boundary rules affect the characteristics of the participants.
2. Position rules differentially affect the capabilities and responsibilities of those in positions.
3. Authority rules affect the actions that participants in positions may, must, or must not do.
4. Scope rules affect the outcomes that are allowed, mandated, or forbidden.
5. Aggregation rules affect how individual actions are transformed into final outcomes.
6. Information rules affect the kind of information present or absent in a situation.
7. Payoff rules affect assigned costs and benefits to actions and outcomes.

Given the nonlinearity and complexity of action situations, it is rarely easy to predict what effect a change in a particular rule will produce. For example, a change in a boundary rule to restrict the entry of appropriators reduces the number of individuals who are tempted to break authority rules, but it also reduces the number of individuals who monitor what is happening or contribute funds toward hiring a guard. Thus, the opportunities for rule breaking may increase. Further, the cost of a rule infraction will be spread over a smaller group of appropriators, and thus the harm to any individual may be greater. Assessing the overall effects of a change in boundary rules is a nontrivial analytical task (for examples, see Weissing & Ostrom 1991a,b). Instead of conducting such a complete analysis, appropriators are more apt to use their intuitive understanding of the resource and each other to experiment with different rule changes until they find a combination that seems to work in their setting.

To understand better the types of tools that are available to appropriators, let us examine in some detail the kind of boundary, authority, payoff, and position rules used in field settings. These four clusters of rules are the major tools used to affect appropriation situations in many common-pool resources, whereas information, scope, and aggregation rules are utilized to complement changes induced by these four rules.

For the past 14 years, colleagues at or associated with the Workshop in Political Theory and Policy Analysis at Indiana University have studied a very large number of irrigation systems, forests, inshore fisheries, and groundwater basins, as well as other common-pool resources (see Schlager 1990; Tang 1992; Schlager et al 1994; Lam 1998; E Ostrom 1990, 1996; Gibson et al 1999). We have collected an immense archive of original case studies con-

**Table 1** Variables used in boundary rules to define who is authorized to appropriate from a resource

| Residency or membership | Personal characteristics | Relationship with resource |
|---|---|---|
| National | Ascribed | Continued use of resource |
| Regional | Age | |
| Local community | Caste | Long-term rights based on: |
| Organization (e.g. co-op) | Clan | Ownership of a proportion of annual flow of resource units |
| | Class | |
| | Ethnicity | Ownership of land |
| | Gender | Ownership of non-land asset (e.g. berth) |
| | Race | |
| | Acquired | Ownership of shares in a private organization |
| | Education level | |
| | Skill test | Ownership of a share of the resource system |
| | | Temporary use-rights acquired through: |
| | | Auction |
| | | Per-use fee |
| | | Licenses |
| | | Lottery |
| | | Registration |
| | | Seasonal fees |
| | | Use of specified technology |

ducted by many different scholars on all sectors in all parts of the world (Martin 1989/1992, Hess 1996, see http://www.indiana.edu/~workshop). Using the IAD framework, we developed structured coding forms to help us identify the specific kinds of action situations faced in the field as well as the types of rules that users have evolved over time to try to govern and manage their resources effectively. In order to develop standardized coding forms, we read hundreds of cases describing how local common-pool resources were or were not regulated by a government agency, by the users themselves, or by a nongovernmental organization (NGO).

## *Affecting the Characteristics of Users through Boundary Rules*

Boundary rules affect the types of participants with whom others interact. An important way of enhancing the likelihood of using reciprocity norms in a commons is to increase the proportion of participants who are well known in a community, have a long-term stake in that community, and find it costly to have their reputation for trustworthiness harmed in that community. Reducing the number of users but opening the resource to strangers willing to pay a license fee, as is frequently recommended in the policy literature, introduces participants who lack a long-term interest in the sustainability of a particular resource, reduces the level of trust and willingness to use reciprocity, and thus increases enforcement costs substantially.

As shown in Table 1, we identified 27 boundary rules described by case-study authors as having been used in at least one common-pool resource somewhere in the world (E Ostrom et al 1989). Although some systems use only a single boundary rule, many use two or three of these rules in combination. Boundary rules can be broadly classified in three general groups defining how individuals gain authority to enter and appropriate resource units from a common-pool resource. The first type of boundary rule relates to an individual's citizenship, residency, or membership in a particular organization. Many forestry and fishing user groups require members to have been born in a particular location. A second broad group of rules relates to individual ascribed or acquired personal characteristics. User groups may stipulate that appropriation depends on ethnicity, clan, or caste. A third group of boundary rules relates to the relationship of an individual with the resource itself. Using a particular technology or acquiring appropriation rights through an auction or a lottery are examples of this type of rule. About half of the rules relate to the characteristics of the users themselves. The other half involve diverse relationships with the resource.

In a systematic coding of case studies about inshore fisheries in many parts of the world, Schlager (1990, 1994) coded 33 user groups out of the 44 groups identified as having at least one rule regarding the use of the resource. All 33 groups used some combination of 14 different boundary rules (Schlager 1994:258). None of these groups relied on a single boundary rule. Thirty out of 33 groups (91%) limited fishing to those individuals who lived in a nearby community, and 13 groups also required membership in a local organization. This indicates that most inshore fisheries organized by the users themselves restrict fishing to those individuals who are well known to each other, have a relatively long-term time horizon, and are connected to one another in multiple ways (see Taylor 1982, Singleton & Taylor 1992).

After residency, the next most frequent type of rules, used in two thirds of the organized subgroups, involved the type of technology that a potential fisher must use. These rules are often criticized by policy analysts, since gear restrictions tend to reduce the "efficiency" of fishing. Gear restrictions have many consequences, however. Used in combination with authority rules that assign fishers using one type of gear to one area of the fishing groups and fishers using another type of gear to a second area, gear restrictions solve conflicts among incompatible technologies. Many gear restrictions also reduce the load on the fishery itself and thus help to sustain longer-term use of the resource.

Other rules were also used by the groups in Schlager's study. A scattering of groups used ascribed characteristics—age (two groups), ethnicity (three groups), or race (five groups). Three types of temporary-use rights included government licenses (three groups), lottery (five groups), and registration (four groups). Seven groups required participants to have purchased an asset, such as a fishing berth, and three groups required ownership of nearby land. Schlager did not find that any particular boundary rule was correlated with higher performance levels, but she did find that the 33 groups who had at least one boundary rule tended to be able to solve common-pool problems more effectively than the 11 groups who had not crafted boundary rules.

In a closely related study of 43 small- to medium-sized irrigation systems managed by farmers or by government agencies, Tang (1992) found that the variety of rules used in irrigation was smaller than among inshore fisheries. The single most frequently used boundary rule, used in 32 of the 43 systems (74%), was that an irrigator must own land in the service area of an irrigation system (Tang 1992:84–85). All of the government-owned and -operated irrigation systems relied exclusively on this rule. Many of the user-organized systems relied on other rules or land ownership combined with other rules. Among the other rules used were ownership of a proportion of the flow of the resource, membership in a local organization, and payment of a per-use fee. Tang (1992:87) found a strong negative relationship between performance and reliance on land as the sole boundary requirement. Over 90% of the systems using other boundary rules, or a combination of rules including land ownership, were rated positively in the level of maintenance achieved and in the level of rule conformance, while less than 40% of those systems relying solely on land ownership were rated at a higher performance level ($P = 0.001$).

This paradoxical result can be understood by a deeper analysis of the incentives facing engineers who design irrigation systems. Many government systems are designed on paper to serve an area larger than they are actually able to

**Table 2** Types of authority rules

| Allocation formula for appropriation rights | Basis for allocation formula |
|---|---|
| Percentage of total available units per period | Amount of land held |
| Quantity of resource units per period | Amount of historical use |
| Location | Location of appropriator |
| Time slot | Quantity of shares of resource owned |
| Rotational order | Proportion of resource flow owned |
| Appropriate only during open seasons | Purchase of periodic rights at auction |
| Appropriate only resource units meeting criteria | Rights acquired through periodic lottery |
| Appropriate whenever and wherever | Technology used |
| | License issued by a governmental authority |
| | Equal division to all appropriators |
| | Needs of appropriators (e.g. type of crop) |
| | Ascribed characteristic of appropriator |
| | Membership in organization |
| | Assessment of resource condition |

serve when in operation, due to a variety of factors, including the need to show as many posited beneficiaries as possible to justify the cost of construction and to gain user support (see Palanisami 1982, Repetto 1986). The government must then use ownership in the authorized service area as the criterion for having a right to water. After construction, authorized irrigators find water to be very scarce because of the unrealistic plans. They are unwilling to abide by authority rules or contribute to the maintenance of the system because of the unpredictability of water availability.

Many of the rich diversity of boundary rules used by appropriators in the field attempt to ensure that the appropriators will relate to others who live nearby and have a long-term interest in sustaining the productivity of the resource. One way of coping with the commons is thus to change the composition of those who use a common-pool resource so as to increase the proportion of participants who have a long-term interest in sustaining the resource, who are likely to use reciprocity, and who can be trusted. Central governments tend to use a smaller set of rules, and some of these may open up a resource to strangers without a longer-term commitment to the resource or may generate conflict and an unwillingness to abide by any rules.

### *Affecting the Set of Allowable Actions through Authority Rules*

Authority rules are also a major type of rule used to regulate common-pool resources. In the coding manual, we identified a diversity of authority rules used in field settings. Some rules involve a simple formula. Many forest resources, for example, are closed to all forms of harvesting during one portion of the year and open for extraction by all who meet the boundary rules during an open season. Most authority rules, however, have two components. In Table 2, the eight allocation formulas used in the field are shown in the left column. A fisher might be assigned to a fixed location (a fishing spot) or to a fixed rotational schedule; a member of the founding clan may be authorized to cut timber anywhere in a forest; an irrigator might be assigned to a fixed percentage of the total water available during a season or to a fixed time slot. In addition to the formula used in an authority rule, most rules required a basis for the assignment. For example, a fisher might be assigned to a fixed location based on a number drawn in a lottery, the purchase of that spot in an auction, or his or her historical use. An irrigator might be assigned to a fixed rotation based on the amount of land owned, the amount of water used historically, or the specific location of the irrigator.

If all of the bases were likely to be combined with all of the formulas, there would be 112 different authority rules (8 allocation formulas × 14 bases). A further complication is that the rules for one product may differ from those for another product in the same resource. In regard to forest resources, for example, children may be authorized to pick fruit from any tree located in a forest if it is for their own consumption; women may be authorized to collect so many headloads of dead wood for domestic firewood and certain plants for making crafts; *shaman* may be the only ones authorized to collect medicinal plants from a particular location in a forest (Fortmann & Bruce 1988). Appropriation rights to fish are frequently related to a specific species. Thus, the exact number of rules that are actually used in the field is difficult to compute because not all bases are used with all formulas, but many rules focus on specific products. A still further complication is that the rules may regularly change over the course of a year depending on resource conditions.

Schlager (1994:259–60) found that all 33 organized subgroups used one of the five basic formulas in their authority rules. Every user group included in her study assigned fishers to fixed locations using a diversity of bases including technology, lottery, and historical use. Thus, spatial demarcations are a critical variable for inshore fisheries. Nine user groups required fishers to limit their harvest to fish that met a specific size requirement, while seven groups allocated fishers to fishing spots using a rotation system and seven other groups only allowed fishing locations to be used during a specific season. Four groups allocated fishing spots for a particular time period (a fishing day or a fishing season).

An important finding—given the puzzles addressed in this chapter—is that the authority rule most frequently recommended by policy analysts (see Anderson 1986, 1992; Copes 1986) is not used in any of the coastal fisheries included in Schlager's study. No attempt was made "by the fishers involved to directly regulate the quantity of fish harvested based on an estimate of the yield. This is particularly surprising given that the most frequently recommended policy prescription made by fishery economists is the use of individual transferable quotas based on estimates on the economically optimal quantity of fish to be harvested over the long run" (Schlager 1994:397). In an independent study of 30 traditional fishery societies, Wilson and colleagues also noted the surprising absence of quota rules (Acheson et al 1998:397; see Wilson et al 1994):

> All of the rules and practices we found in these 30 societies regulate "how" fishing is done. That is, they limit the times fish may be caught, the locations where fishing is allowed, the technology permitted, and the stage of the life cycle during which fish may be taken. None of these societies limits the "amount" of various species that can be caught. Quotas—the single most important concept and tools of scientific management—is conspicuous by its absence.

Local inshore fishers, when allowed to manage a riparian area, thus use rules that differ substantially from those recommended by advocates of scientific management. Fishers have to know a great deal about the ecology of their inshore region, including spawning areas, nursery areas, the migration routes of different species, and seasonal patterns, just to succeed as fishers. Over time, they learn how "to maintain these critical life-cycle processes with rules controlling technology, fishing locations, and fishing times. Such rules in their view are based on biological reality" (Acheson et al 1998:405).

In the irrigation systems studied by Tang (1992:90–91), three types of authority rules are used most frequently: (*a*) a fixed time slot for each irrigator (19 out of the 37 cases for which data is available, and in 10 out of 12 government-owned systems), (*b*) a fixed order for a rotation system among irrigators (13 cases), and (*c*) a fixed percentage of the total water available during a period of time (5 cases). Three poorly performing systems with high levels of conflict use no authority rule at all. A variety of bases were used in these rules, such as "amount of land held, amount of water needed to cultivate existing crops, number of shares held, location of field, or official discretion" (Tang 1994:233). Farmers also do not use rules that assign a specific quantity of water to irrigators except in the rare circumstances where they control substantial amounts of water in storage (see Maass & Anderson 1986). Fixed-time-slot rules allow farmers considerable certainty as to when they will receive water without an equivalent certainty about the quantity of water that will be available in the canal. When the order is based on a share system, simply owning land next to an irrigation system is not enough. A farmer must purchase one or more shares to irrigate for a particular time period. Fixed-time allocation systems, which are frequently criticized as inefficient, do economize greatly on the amount of knowledge farmers have to have about the entire system and on monitoring costs. Spooner (1974) and Netting (1974) described long-lived irrigation systems in Iran and in Switzerland where there was perfect agreement on the order and time allotted to all farmers located on a segment of the system, but no one knew the entire sequence for the system as a whole.

Tang also found that many irrigation systems use different sets of rules depending on the availability of water. During the most abundant season, for example, irrigators may be authorized to take water whenever they need it. During a season when water availability is moderate, farmers may use a rotation system in which every farmer is authorized to take water for a fixed amount of time during the week based on the amount of land to be irrigated. During scarcity, the irrigation system may employ a special water distributor who is authorized to allocate water to those farmers who are growing crops authorized by the irrigation system and are most in need.

The diversity of rules devised by users greatly exceeds the limited authority rules that are recommended in textbook treatments of this problem. Appropriators thus cope with the commons by using a wide variety of rules that affect the actions available to participants and thus affect their basic set of strategies. Given this wide diversity of rules, it is particularly noteworthy that rules assigning appropriators a right to a specific quantity of a resource are used so infrequently in inshore fisheries and irrigation systems. [They are used more frequently when allocating forest products, where both the quantity available and the quantity harvested are much easier to measure (Agrawal 1994).] To assign an appropriator a specific quantity of a resource unit requires that those making the assignment know the total available units. In water resources where there is storage of water from one season to another and reliable information about the quantity of water is available, such rules are more frequently utilized (Blomquist 1992, Schlager et al 1994).

## *Affecting Outcomes through Payoff and Position Rules*

One way to reduce or redirect the appropriations made from a common-pool resource is to change payoff rules so as to add a penalty to actions that are prohibited. Many user groups also adopt norms that rule breakers should be socially ostracized or shunned, and individual appropriators tend to monitor each other's behavior rather intensively. Three broad types of payoff rules are used extensively in the field: (*a*) the imposition of a fine, (*b*) the loss of appropriation rights, and (*c*) incarceration. The severity of each of these types of sanctions can range from very low to very high and tends to start out on the low end of the scale. Inshore fisheries studied by Schlager relied heavily on shunning and other social norms and less on formal sanctions. Thirty-six of the 43 irrigation systems studied by Tang used one of these three rules and also relied on vigorous monitoring of each other's behavior and shunning of rule breakers. The seven systems that did not self-consciously punish rule infractions were all rated as having poor performance. Fines were most typically used (in 21 cases) and incarceration the least (in only 2 cases). Fines tend to be graduated depending on the seriousness of the infractions and the number of prior infractions. The fines for a first or second offense tended to be very low.

Passing rules that impose costs is relatively simple. The difficult task is monitoring behavior to ascertain if rules are being broken. Self-organized fisheries tend to rely on self-monitoring more than the creation of a formal position of guard. Most inshore fishers now use short-wave radios as a routine part of their day-to-day operations, allowing a form of instant monitoring to occur. An official of a West Coast Indian tribe reports, for example, that "it is not uncommon to hear messages such as 'Did you see so-and-so flying all that net?' over the short-wave frequency—a clear reference to a violation of specified gear limits" (cited in Singleton 1998:134). Given that most fishers will be listening to their short-wave radios, "such publicity is tantamount to creating a flashing neon sign over the boat of the offender. Such treatment might be proceeded [sic] or followed by a direct approach to the rule violator, advising him to resolve the problem. In some tribes, a group of fishermen might delegate themselves to speak to the person" (cited in Singleton 1998:134).

Among self-organizing forest governance systems, creating and supporting a position as guard is frequently essential because resource units are highly valuable and a few hours of stealth can generate substantial illicit income. Monitoring rule conformance among forest users by officially designated and paid guards may make the difference between a resource in good condition and one that has become degraded. In a study of 279 forest *panchayats* in the Kumaon region of India, Agrawal & Yadama (1997) found that the number of months a guard was on duty was the most important variable affecting forest conditions. The other variables that affected forest conditions included the number of meetings held by the forest council (a time when infractions were discussed) and the number of residents in the village.

> It is evident from the analysis that the capacity of a forest council to monitor and impose sanctions on rule-breakers is paramount to maintaining the forest in good condition. Nor should the presence of a guard be taken simply as a formal mechanism that ensures greater protection. It is also an indication of the informal commitment of the *panchayat* and the village community to protect their forests. Hiring a guard costs money. The funds have to be generated within the village and earmarked for protection of the resource. If there was scant interest in protecting the forest, villagers would have little interest in setting aside the money necessary to hire a guard. (Agrawal & Yadama 1997:455)

Whether an irrigation system creates a formal position as guard depends both on the type of governance of the system and on its size. Of the 15 government-owned irrigation systems included by Tang (1992), 12, or 80%, have established a position of guard. Stealing water was a problem on most government-owned systems, but it was endemic on the three systems without guards. Of the 28 farmer-organized systems, 17 (61%) utilized the position of water distributor or guard. Of the 11 farmer-organized systems that did not employ a guard, farmers on 5 systems (45%) were vigilant enough in monitoring each other's activities that rule conformance is high. That means, of course, that self-monitoring was not sufficient on the other 6 systems to support routine conformance with their own rules. A study of 51 communal irrigation systems in the Philippines illustrated the effect of size (de los Reyes 1980). Of the 30 systems that were less than 50 hectares, only 6 (20%) had established a position of guard; of the 11 systems that served between 50 and 100 hectares, 5 (45%) had established guards; and of the 10 systems over 100 hectares, 7 (70%) had created guards. De los Reyes also found, in a survey of over 600 farmers served by these communal irrigation systems, that most farmers also patrolled their own canals even when they were patrolled by guards accountable to the farmers for distributing water. Further, the proportion of farmers who reported patrolling the canals serving their farms increased to 80% on the largest self-organized systems compared with 60% on the smallest systems.

Creating the position of guard also requires a change in payoff rules so that the guard can be remunerated. Several formulas are used. On government-owned irrigation systems, guards are normally paid a monthly wage that is not dependent on the performance of a system or on farmers' satisfaction. Wade (1994) describes self-organized systems in South India where the water distributor–guard is paid in kind as the harvest is reaped by going to each farmer to collect his share based on the amount of land owned by the farmer. Sengupta (1991:104) describes another system in which, immediately after appointment, the guards "are taken to the temple for oath taking to remain impartial. With this vow, they break a coconut. They are paid in cash at the rate of Rs 10 per acres...per month by the cultivators. The *neerpaichys* themselves collect the money." With such subtle ways of changing the way the payment is made to this position, farmers are able to monitor the monitor more effectively.

Boundary and authority rules also affect how easy or difficult it is to monitor activities and impose sanctions on rule infractions. Closing a forest or an inshore fishery for a substantial amount of time, for example, has multiple impacts. It protects particular plants or fish during critical growing periods and allows the entire system time to regenerate without disturbance. Further, during the closed season, rule infractions are obvious to anyone, since any appropriator in the resource is almost certainly breaking the rules. Similarly, requiring appropriators to use a particular technology may reduce the pressure on the resource, help to solve conflicts among users of incompatible technologies, and make it very easy to ascertain if rules are being followed. Many irrigation systems set up rotation systems so that only two persons need to monitor actions at any one time and thus keep monitoring costs lower than they would otherwise be. Changing payoff rules is the most direct way of coping with commons dilemmas. In many instances, dilemma games can be transformed into assurance games—a much easier situation to solve.

### *Affecting Outcomes through Changes in Information, Scope, and Aggregation Rules*

These rules tend to be used in ways that complement changes in boundary, authority, payoff, and position rules. Individual systems vary radically in regard to the mandatory information that they require. Many smaller and informal systems rely entirely on a voluntary exchange of information and on mutual monitoring. Where resource units are very valuable and the size of the group is larger, more and more requirements are added regarding the information that must be kept by appropriators or their officials. Scope rules are used to limit harvesting activities in some regions that are being treated as refugia. If no appropriation from these locations is allowed, the regenerative capacity of a system can be enhanced. Aggregation rules are used extensively in collective-choice processes and less extensively in operational settings, but one aggregation rule that is found in diverse systems is a requirement that harvesting activities be done in teams. This increases the opportunity for mutual monitoring and reduces the need to hire special guards.

It is important to note that we have not yet found any particular rules to have a statistically positive relationship to performance. The absence of any boundary or authority rule, however, is consistently associated with poor performance. Relying on a single type of rule for an entire set of common-pool resources is also negatively related to performance. Although specific rules are not systematically related to performance, self-governed systems appear to have two advantages in adopting rules to fit a local resource—more knowledge of the resource and efficient monitoring options.

## POLICIES AS EXPERIMENTS

### *The Daunting Search for Better Rules*

It should now be obvious that the search for rules that improve the outcomes obtained in commons dilemmas is an incredibly complex task involving a potentially infinite combination of specific rules that could be adopted. To ascertain whether one has found an optimal set of rules to improve the outcomes achieved in a single situation, one would need to analyze how diverse rules affect each of the seven components of such a situation, and, as a result, the likely effect of a reformed structure on incentives, strategies, and outcomes. Because there are multiple rules that affect each of the seven components, conducting such an analysis would be an incredibly time- and resource-consuming process. For example, if only five changes in rules per component were considered, there would be $5^7$, or 75,525, different situations to analyze. This is a gross simplification, however, since some of the important rules used in field settings include more than five rules—at least 25 in the case of boundary rules, and over 100 variants in the case of authority rules. Further, how these changes affect the outcomes achieved in a particular location depends on the biophysical characteristics of that location and the type of community relationships that already exist. No set of policy analysts (or even all of the game theorists in the world today) could ever have sufficient time or resources to analyze over 75,000 combinations of rule changes and resulting situations, let alone all of the variance in these situations due to biophysical differences.

### *Experimenting with Rule Changes*

Instead of assuming that designing rules that approach optimality, or even improve performance, is a relatively simple analytical task that can be undertaken by distant, objective analysts, we need to understand the policy design process as involving an effort to tinker with a large number of component parts (see Jacob 1977). Those who tinker with any tools—including rules—are trying to find combinations that work together more effectively than other combinations. Policy changes are experiments based on more or less informed expectations about potential outcomes and the distribution of these outcomes for participants across time and space (Campbell 1969, 1975). Whenever individuals agree to add a rule, change a rule, or adopt someone else's proposed rule set, they are conducting a policy experiment. Further, the complexity of the ever-changing biophysical world combined with the complexity of rule systems means that any proposed change of rules faces a nontrivial probability of error.

With each policy change, when there is only a single governing authority, policy makers tend to experiment simultaneously with all of the common-pool resources within their jurisdiction. A central government can undertake pilot programs to experiment with various options, but the intent is usually to find the set of rules that work best for an entire jurisdiction. The process of experimentation is usually slow. Information about results may be contradictory and difficult to interpret. Thus, an experiment that is based on erroneous data about one key structural variable or one false assumption about how actors will react can lead to a very large disaster (see Wilson et al 1999). In any design process that involves substantial probability of error, having redundant teams of designers has been shown to be advantageous (see Landau 1969; 1973, Bendor 1985).

## SELF-ORGANIZED RESOURCE GOVERNANCE SYSTEMS AS COMPLEX ADAPTIVE SYSTEMS

As discussed in the introduction, many scholars consider the very concept of organization to be closely tied to the presence of a central director who has designed a system to operate in a particular way. Consequently, the mechanisms used by organized systems that are not centrally directed are not well understood in many cases. Many self-organized resource governance systems are invisible to the officials of their own country or those from donor agencies. A classic example of this occurred in the Chitwan valley of Nepal several years ago, when an Asian Development Bank team of irrigation engineers recommended a large loan to build a dam across the Rapti River to enable the farmers there to irrigate their crops. What the engineering design team did not see were the 85 farmer-managed irrigation systems that already existed in the valley and had achieved relatively high performance. Most farmers in the Chitwan valley already obtained three irrigated crops a year as a result of their participation in the activities of these irrigation systems (see Benjamin et al 1994).

In contrast to forms of organization that result from central direction, most self-organized groups—including the types of locally organized fisheries, forests, grazing areas, and irrigation systems discussed in this chapter—are better viewed as complex adaptive systems. Complex adaptive systems are composed of a large number of active elements whose rich patterns of interactions produce emergent properties that are not easy to predict by analyzing the separate parts of a system. Holland (1995:10) views complex adaptive systems as "systems composed of interacting agents described in terms of rules. These agents adapt by changing their rules as experience accumulates." Complex adaptive systems "exhibit coherence under change, via conditional action and anticipation, and they do so without central direction" (Holland 1995:38–39). Holland points out that complex adaptive systems differ from physical systems that are not adaptive and that have been the foci of most scientific effort. It is the physical sciences that have been the model for many aspects of contemporary social science. Thus, the concepts needed to understand the adaptivity of systems are not yet well developed by social scientists.

## *Properties and Mechanisms of Complex Adaptive Systems*

No general theory of complex adaptive systems yet exists to provide a coherent explanation for processes shared by all such systems. Biologists have studied many different adaptive systems but within separate fields of biology. Thus, even biologists have not recognized some of the similarities of structures and processes that characterize the central nervous system, the immune system, and the evolution of species. Recent work at the Sante Fe Institute has begun to identify central attributes, mechanisms, and processes used by all complex adaptive systems, including biological systems as well as markets and other social systems that are not centrally directed (Anderson et al 1988).

It appears that complex adaptive systems share four basic properties: nonlinearity, flows, diversity, and aggregation. The first three properties clearly characterize the types of self-organized resource governance systems discussed in this chapter involving nonlinear flows of diverse products from common-pool resources. The term aggregation refers to the "emergence of complex larger-scale behavior from the aggregate interactions of less complex agents" (Holland 1995:11). For example, many irrigation systems are divided into several tiers and multiple units at each tier. All of the farmers on a field channel are responsible for distributing the water to this small channel as well as keeping it in good repair. All farmers whose field channels are served by a branch canal may send a representative to a branch canal organization that focuses on the distribution of water among all branches and on the maintenance of the distribution canals. The branch canal organization may send a representative to a central committee that is responsible for the headworks that divert the water from a river into the system in the first place. The rules used on one branch canal or one field channel may be quite different from the rules used on others. There is no single center of authority for these systems that makes all relevant decisions on how to get water from the river to a farmer's field, but in many farmer-organized systems, the water is distributed in an organized fashion and all of the waterworks are maintained as a result of the aggregation of decisions and actions at multiple levels (see Yoder 1994; E Ostrom 1992; Coward 1979, 1985; Wade 1988).

In addition to these four attributes, complex adaptive systems also use three mechanisms that are key to the adaptive process itself. These include the use of tags, internal models, and building blocks.

THE USE OF TAGS Tagging is a universal mechanism for boundary formation and aggregation of units in complex adaptive systems. "Tags are a pervasive feature of [complex adaptive systems] because they facilitate selective interactions. They allow agents to select among agents or objects that would otherwise be indistinguishable" (Holland 1995:14). All rules involve tags of some sort. The boundary rules shown in Table 1 involve the specification of the tags that are used to determine who is authorized to be a co-appropriator from a common-pool resource. Residency, prior membership, and personal characteristics are attributes that already exist and are easy to use as boundary tags. Boundary rules that focus on an individual's relationship with a resource are acquired specifically related to that resource. Local governance systems rely heavily on tags that identify individuals who are already known to each other, who have a long-term stake in the sustainability of a resource, who have an incentive to build a reputation for being trustworthy, and who are thus likely to extend reciprocity rather than recalcitrance in dealing with joint problems.

Tags are also used extensively to mark locations in a resource, to warn rule breakers, and even to mark individual organisms that need to be treated in a special way. An example of the latter occurs along the Maine coast, where it is forbidden to harvest berried lobsters (those with eggs). Such lobsters are V-notched and returned to the sea (Acheson 1988, 1989). Any fisherman who captures a V-notched lobster is also supposed to return it to the sea. If someone has put a lobster trap in the wrong place, Maine lobstermen tie a rope on the trap in a noticeable location to warn the fisher that his infraction has been noticed. If a fisher ignores this initial warning, the lobster traps themselves are likely to be destroyed the next time they are noticed in the wrong location.

INTERNAL MODELS The appropriators from a common-pool resource build internal models of the resource, the relationships among the components of the resource, and frequently where their own actions are positively or negatively related to one another and the resource. Among the shared lore for most fishing villages is a clear understanding of where fish breed, where young fish tend to cluster, the length of time it takes for fish to be mature and reproduce, the migration patterns of fish, the food chain in a location, etc. Many inshore fishers develop their own maps of all of the fishing spots in their grounds (see, for example, Berkes 1986). In an effort to reduce the interference of one boat with another boat's fishing, these are frequently defined so that if all fishing spots are filled, all boats are still able to have a good chance to catch fish. These maps are then used in a variety of allocation rules that specify how any particular boat is assigned to a particular fishing spot. Users of forests also map their forests and may create refugia—sometimes as sacred forests—for sections that are particularly rich in biodiversity. By not harvesting from these refugia, users maintain a source of regeneration for other nearby locations that are disturbed through harvesting. Similarly, farmers who manage their own irrigation systems have clear mental (and frequently, paper) maps of these physical systems. These system models are called upon when maintenance responsibilities are allocated, so that their more vulnerable locations are assigned more time and resources than locations that are stable without much maintenance.

BUILDING BLOCKS Building blocks are ways of breaking down complex processes into small chunks that can be used in multiple ways and can be combined and recombined repeatedly and at diverse levels. Once an authority rule that allocates resource units on some basis is determined, for example, using the same basis again to allocate responsibility for maintenance work is considered to be a fair allocation of benefits and costs in many cultures and is relatively easy to remember. On the large Chhattis Mauja farmer-organized system in Nepal, for example, water was originally allocated by the land area served. In the 1950s, the formula used for maintenance work was that each branch canal was responsible for sending one person to work on the main canal for each 17 hectares of area it irrigated. "The term used for a person-day of labor for canal maintenance was *kulara*. Since the share of water a branch canal is entitled to receive is the same as the resource mobilization requirement, water allocation is now also referred to as 'so many *kulara* of water'" (Yoder 1991:7). As the system has grown, the total number of *kulara* has now been set at 177 shared among 44 branch canals. Voting rights are now also set in terms of *kulara*. "Therefore, a branch canal with five *kulara* was entitled to 5/177 of the water in the main canal, responsible to supply 5/177 of the resources mobilized for the irrigation, and had five of the total 177 votes in all important decisions" (Yoder 1991:7).

## *Changing Rules as an Adaptive Process*

Given the logic of combinatorics, it is impossible—as shown above—to conduct a complete analysis of the expected performance of all of the potential rule changes that could be made by the individuals served by a self-organized resource governance system trying to improve its performance. A similar impossibility also exists for many biological systems. Let us explore these similarities.

Self-organizing resource governance systems have two structures that are somewhat parallel in their function to the concepts of a genotype and a phenotype in biology. Phenotypic structures characterize an expressed organism—how bones, organs, and muscles develop, relate, and function in an organism in a particular environment. The components of an action situation characterize an expressed situation—how the number of participants, the information available, and their opportunities and costs create incentives, and how incentives lead to types of outcomes in a particular environment. The genotypic structure characterizes the set of instructions encoded in DNA to produce an organism with a particular phenotypic structure. A rule configuration is a set of instructions on how to produce the structure of relationships among individuals in an action situation that is also affected by the biophysical world and the kind of community or culture in which an action situation is located.

The evolution of social systems does not follow the same mechanisms as the evolution of species (Boyd & Richerson 1985, Campbell 1975, Nelson & Winter 1982). In any evolutionary process, there must be the generation of new alternatives, selection among new and old combinations of structural attributes, and retention of those combinations of attributes that are successful in a particular environment. In evolving biological systems, genotypic structures are changed through mechanisms such as crossover and mutation, and the distribution of particular types of instructions depends on the survival rate of the phenotypes they produce in given environments. Instead of blind variation, human agents do use reason and persuasion in their efforts to devise better rules, but the process of choice always involves experimentation. Self-organized resource governance systems use many types of decision rules to make collective choices. These range from deferring to the judgment of one person or elders, to using majority voting, to relying on unanimity. The subject of what collective-choice rules are better for coping with tragedies of the commons is too large to discuss here.

Most systems are likely to start with one or two simple rules. An obvious first candidate is to use tags to close the boundary to outsiders in order to enhance the likelihood of contingent cooperation and conformance to agreements. By changing only a few rules at the beginning, everyone can come to understand those rules while evaluating how they work. A second candidate is to use the shared model of the environment built up through years of interaction in an environment to refine where appropriation should be undertaken and when. Space and time are candidates for allocating access to resources in a manner that is relatively low-cost to sustain. If the community is small enough and shares common norms at a high enough level, it may be unnecessary to create formal sanctions, guards, records, and other rules.

Changes in specific rules may come about through accident (forgetting or innovating on the spot) or through specific collective-choice processes, in which considerable time and effort are devoted to considering why performance needs to be enhanced and which rules might be changed. Since many appropriators have experience with more than one product, rules tried in regard to one product may be tried in regard to others if they are successful. Migration of individuals into a community brings individuals with repertoires of different rules used in other locations. Commerce with other groups lets appropriators see and learn about other groups who may be doing better (or worse) than they are in regulating a sustainable and efficient resource system. Thus, a self-organized resource governance system with a higher level of in-migration or greater communication with other localities is more likely to adapt and change rules over time than is a system where new ideas concerning how to use rules as tools are rarely brought in. Trial-and-error processes may give relatively rapid feedback about rules that obviously do not work in a particular environment, but this is not always the case when the effect of human action on the environment has a long time delay. If all self-organized resource governance systems are totally independent and there is no communication among them, then each has to learn through its own trial-and-error process. Many will find that rules that they have tried do not work. Some will fail entirely.

The rate of change differs among self-organized resource governance systems. As with all learning theories, the rate of change is an important variable affecting performance over time. If change occurs too rapidly, little is learned from each experiment before another experiment is launched. Respect for tradition and even religious mystification has been used to increase the retention of rules considered effective by at least some participants. If the heavy hand of tradition is too heavy, however, and innovation is stymied, a system that was well adapted to a past environment may find itself faltering as external changes occur without adaptation.

## THE ADVANTAGES AND LIMITS OF PARALLEL SETS OF LOCAL USERS IN POLICY EXPERIMENTS

The last major task of this chapter is to discuss why a series of relatively autonomous, self-organized resource governance systems may do a better job of regulating small common-pool resources than a single central authority. In such systems, individuals who have the greatest interest in overcoming tragedies of the commons learn the results of their experimentation with rules and can adapt to this direct feedback. In this section, I discuss the advantages and limits of a fully decentralized system, where all responsibility for making decisions related to smaller-scale common-pool resources is localized. In the final section, I discuss why a polycentric governance system involving higher levels of government as well as local systems is able to cope even more effectively with tragedies of the commons.

Among the advantages of authorizing the users of smaller-scale common-pool resources to adopt policies regulating the use of these resources are the following:

1. Local knowledge. Appropriators who have lived and appropriated from a resource system over a long period of time have developed relatively accurate mental models of how the biophysical system itself operates, since the very success of their appropriation efforts depends on such knowledge. They also know others living in the area well and know what norms of behavior are considered appropriate by this community.
2. Inclusion of trustworthy participants. Appropriators can devise rules that increase the probability that others are trustworthy and will use reciprocity. This lowers the cost of relying entirely on formal sanctions and paying for extensive guarding.
3. Reliance on disaggregated knowledge. Feedback about how the resource system responds to changes in actions of appropriators is generated in a disaggregated way. Fishers are quite aware, for example, when the size and species distribution of their catch changes over time. Irrigators learn whether a particular allocation system is efficient by comparing the net yield they obtain under one set of rules versus others.
4. Better adapted rules. Given the above, appropriators are more likely to craft rules that are better adapted to each of the local common-pool resources than any general system of rules.
5. Lower enforcement costs. Because local appropriators have to bear the cost of monitoring, they are apt to craft rules that make infractions highly obvious so that monitoring costs are lower. Further, by creating rules that are seen as legitimate, appropriators encourage higher conformance.
6. Redundancy. Multiple units are experimenting with rules simultaneously, thereby reducing the probability of failure for an entire region.

There are, of course, limits to all ways of organizing the governance of common-pool resources. Among the limits of a highly decentralized system are the following:

1. Some appropriators will not organize. Although the evidence from the field is that many local appropriators do invest considerable time and energy into their own regulatory efforts, other groups of appropriators do not. There appear to be many reasons why some groups do not organize, including the presence of low-cost alternative sources of income and thus a reduced de-

pendency on the resource, conflict among appropriators along multiple dimensions, lack of leadership, and fear of having their efforts overturned by outside authorities.

2. Some self-organized efforts will fail. Given the complexity of the task involved in designing rules, some groups will select combinations of rules that generate failure. They may be unable to adapt rapidly enough to avoid the collapse of a resource system.
3. Local tyrannies may prevail. Not all self-organized resource governance systems will be organized democratically or rely on the input of most appropriators. Some will be dominated by a local leader or a power elite who only make changes that will be an advantage to them. This problem is accentuated in locations where the cost of exit is particularly high and reduced where appropriators can leave.
4. Stagnation may occur. Where local ecological systems are characterized by considerable variance, experimentation can produce severe and unexpected results, leading appropriators to cling to systems that have worked relatively well in the past and stop innovating long before they have developed rules likely to lead to better outcomes.
5. Inappropriate discrimination may result from the use of identity tags. The use of tags is frequently an essential method for increasing the level of trust and rule conformance. Tags based on ascribed characteristics can, however, be the basis of excluding some individuals from access to sources of productive endeavor regardless of their trustworthiness.
6. Access to scientific information may be limited. Although time and place information may be extensively developed and used, local groups may not have access to scientific knowledge concerning the type of resource system involved.
7. Conflict may arise among appropriators. Without access to an external set of conflict-resolution mechanisms, conflict within and across common-pool resource systems can escalate and provoke physical violence. Two or more groups may claim the same territory and may continue to make raids on one another over a long period of time.
8. Appropriators may be unable to cope with larger-scale common-pool resources. Without access to some larger-scale jurisdiction, local appropriators may have substantial difficulties regulating only a part of a larger-scale common-pool resource. They may not be able to exclude others who refuse to abide by the rules that a local group would prefer to use. Given this, local appropriators have no incentives to restrict their own use.

## THE CAPABILITIES OF POLYCENTRIC SYSTEMS IN COPING WITH TRAGEDIES OF THE COMMONS

Many of the capabilities of a parallel adaptive system are retained in a polycentric governance system while obtaining some of the protections of a larger system. By polycentric, I mean a system where citizens are able to organize not just one but multiple governing authorities at differing scales (see V Ostrom et al 1961; V Ostrom 1987, 1991, 1997). Each unit may exercise considerable independence to make and enforce rules within a circumscribed scope of authority for a specified geographical area. In a polycentric system, some units are general-purpose governments, whereas others may be highly specialized (McGinnis 1999a,b,c). Self-organized resource governance systems, in such a system, may be special districts, private associations, or parts of a local government. These are nested in several levels of general-purpose governments that also provide civil equity as well as criminal courts.

In a polycentric system, the users of each common-pool resource would have authority to make at least some of the rules related to the use of that particular resource. Thus, they would achieve many of the advantages of utilizing local knowledge as well as the redundancy and rapidity of a trial-and-error learning process. On the other hand, problems associated with local tyrannies and inappropriate discrimination can be addressed in larger, general-purpose governmental units that are responsible for protecting the rights of all citizens and for the oversight of appropriate exercises of authority within smaller units of government. It is also possible to make a more effective blend of scientific information with local knowledge where major universities and research stations are located in larger units but have a responsibility to relate recent scientific findings to multiple smaller units within their region. Because polycentric systems have overlapping units, information about what has worked well in one setting can be transmitted to others, who may try it out in their settings. Associations of local resource governance units can be encouraged to speed up the exchange of information about relevant local conditions and about policy experiments that have proved particularly successful. And when small systems fail, there are larger systems to call upon—and vice versa.

Polycentric systems are themselves complex adaptive systems without one dominating central authority. Thus, there is no guarantee that such systems will find combinations of rules at diverse levels that are optimal for any particular environment. In fact, one should expect that all governance systems will be operating at less than optimal levels, given the immense difficulty of fine-tuning any very complex, multitiered system.

In the United States, many examples of dynamic, polycentric resource governance systems exist where there is strong evidence of high performance. One example is the Maine lobster fishery, which is noteworthy because of the long-term, complementary roles adopted by both local and state governance systems. Maine is organized into riparian territories along most of the coast. Boundary rules and many of the day-to-day fishing regulations are organized by harbor gangs (Acheson 1988).

> In order to go fishing at all, one must become a member of a "harbor gang," the group of fishermen who go lobstering from a single harbor. Once one has gained admittance into such a group, one can only set traps in the traditional territory of that particular harbor gang. Members of harbor gangs are expected to obey the rules of their gang concerning fishing practices, which vary somewhat from one part of the coast to another. In all areas a person who gains a reputation for molesting others' gear or for violating conservation laws will be severely sanctioned. Incursions into the territory of one gang by fishers from another are ordinarily punished by surreptitious destruction of lobster gear. There is strong statistical evidence that the territorial system, which operates to limit the number of fishers exploiting lobsters in each territory, helps to conserve the lobster resource. (Acheson et al 1998:400)

In addition, the state of Maine has long-established formal laws that protect the breeding stock and increase the likelihood of high regeneration rates. "At present, the most important conservation laws are minimum and maximum size measures, a prohibition against catching lobsters with eggs, and a law to prohibit the taking of lobsters which once had eggs and were marked—i.e. the 'V-notch' law" (Acheson et al 1998:400). Neither the state nor any of the harbor gangs have tried to limit the quantity of lobster captured. The state does not make any effort to limit the number of fishers because this is already done at a local level. However, the state has been willing to intercede when issues exceed the scope of control of local gangs. In the late 1920s, for example, when lobster stocks were at very low levels and many local areas appear to have had substantial compliance problems, the state took a number of steps—including threats to close the fishery—that supported informal local enforcement efforts. By the late 1930s, compliance problems were largely resolved and stocks had rebounded.

Recently, in response to changes that were breaking down the harbor gang system, the state has formalized the system by dividing Maine into zones with democratically elected councils. Each council has been given authority over rules that have principally local impacts—trap limits, days and times fished, etc. Interestingly, the formalization of local zones was followed, almost immediately, by the creation of an informal council of councils to address problems at a greater-than-local scale. It is expected that the council of councils will be formalized soon (Wilson 1997).

Today, the state needs only about six patrol officers on the water to police the activities of 6800 lobstermen, all the other fisheries, and coastal environmental laws. During the 1990s, the fishery has been growing substantially with increased yields (Acheson 1993). At the same time, there is strong evidence that the number of reproductive-age female lobsters in the Maine waters is large and that the recruitment levels will remain high.

The system of co-management of the Pacific salmon fisheries in the state of Washington is another noteworthy example of a recently evolved polycentric system that appears to be working much better than an earlier system that was dominated primarily by state and federal agencies (see Singleton 1998). The change in the system came as a result of a major court decision in the mid-1970s, which stated that the Indian tribes who had signed treaties more than a century earlier had protected rights to 50% of the fish that passed through the normal fishing areas of the tribes. This has required the state to develop a "co-management" system that involves both the state of Washington and the 21 Indian tribes in diverse policy roles related to salmon. This is a large, transboundary resource utilized by major commercial firms as well as by the Indian tribes. The active involvement of the state means that it is "safe" for local groups to agree to follow strong conservation practices because they know that other local groups are involved in the same practices. At the same time, the earlier, centrally regulated system had focused on aggregations of species and spent little time on the fresh-water habitats that are essential to maintain the viability of salmon fisheries over the long term. Individual tribal authorities have concentrated their attention on the specific stocks and their management. Co-management of migrating fishery stocks has also been evaluated as successful in British Columbia and other locations (Pinkerton 1989, Poffenberger & McGean 1996). Alcorn & Toledo (1998) stress the complementary institutional systems at the national level in Mexico, supportive of *ejidos* and *communidades* at a local level, as generating a more sustainable governance system than exists in other, similar ecological conditions.

Coping with potential tragedies of the commons is never easy and never finished. Now that we know that those who depend on these resources are not forever trapped in situations that will only get worse over time, we need to recognize that governance is frequently an adaptive process involving multiple actors at diverse levels. Such systems look terribly messy and are hard to understand. The scholars' love of tidiness must be resisted. Instead, we need to develop better theories of complex adaptive systems, particularly those that have proved themselves able to utilize renewable natural resources sustainably over time.

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