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HUMAN ECOLOGY AND RESOURCE SUSTAINABILITY: The Importance of Institutional Diversity

C. Dustin Becker and Elinor Ostrom

Workshop in Political Theory and Policy Analysis, Indiana University, 513 North Park, Bloomington, Indiana 47408-3895

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ABSTRACT

We define the concept of a common-pool resource based on two attributes: the difficulty of excluding beneficiaries and the subtractability of use. We present similarities and differences among common-pool resources in regard to their ecological and institutional significance. The design principles that characterize long-surviving, delicately balanced resource systems governed by local rules systems are presented, as is a synthesis of the research on factors affecting institutional change. More complex biological resources are a greater challenge to the design of sustainable institutions, but the same general principles appear to carry over to more complex systems. We present initial findings from pilot studies in Uganda related to the effects of institutions on forest conditions.

INTRODUCTION

Aristotle asked how we as political animals could design and create institutions that would assure our survival with "some measure of good life within it." Today, numerous writings on sustainability reflect a shared awareness that natural resources are becoming increasingly scarce. Abnormally high extinction rates, deforestation rates, a thinning ozone layer, and increasing carbon dioxide and water pollution levels are but a few of the vital signs that humanity,

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in its aggregate, has gone beyond a sustainable relationship with Earth's natural resources.

The original scope—that of a city—of Aristotle's question is still relevant. Some of the worst environmental problems on the globe are found in urban slums where local residents have little authority to design and create their own institutions. In addition, the realm of some environmental problems has greatly expanded from the size of a Greek city to the extent of the Earth. Aristotle's question, though, at its heart, remains the same. What multitiered social arrangements would best allow the future billions of us to have the comforts of basic human needs: clean water and air, nutritious foods, shelter, and human dignity? While there is no single answer to this question, general principles can be derived from both ecology and social science that are usable by diverse individuals in multiple settings to create and recreate institutions that will help humans assign more realistic valuations to ecological goods and services, and thereby be more likely to manage these resources in a sustainable manner.

A key challenge is establishing a common ground in the fractured academic world of the natural and social sciences. The discipline of human ecology tries to do this. The concept of common-pool resources and the question of how to govern and manage them, for example, have recently been addressed by many human ecologists (7, 10, 14, 47). In this paper, we define the concept of a common-pool resource based on two attributes: the difficulty of excluding beneficiaries and the subtractability of use. We present similarities and differences among common-pool resources in regard to their ecological and institutional significance. The design principles that characterize long-surviving delicately balanced resource systems governed by local rules systems are presented, as is a synthesis of the research on factors affecting institutional change. More complex biological resources are a greater challenge to the design of sustainable institutions, but the same general principles appear to carry over to more complex systems. We present initial findings from pilot studies in Uganda related to the effects of institutions on forest conditions.

RETHINKING THE TRAGEDY OF THE COMMONS

A decade ago, when the National Academy of Sciences first established a panel to study common-property institutions,[1] many scientists interested in

[1]This was the Panel on Common Property Resources. For publications, see National Research Council (52) and Bromley et al (14). A flurry of books and dissertations have been generated as the result of the Panel's initial activities and findings (7, 10, 12, 13, 23, 34, 38, 39, 45, 47, 54, 56, 57, 60, 63, 64, 69, 73, 74, 85, 86, 89). The International Association for the Study of Common Property, which was formed after the NAS panel finished its activities, will have had its fifth meeting in Bodø, Norway, May 24–28, 1995.

natural resource policy problems presumed that the users of common-pool resources were helplessly caught in a tragedy of the commons. Scientists assumed that users were destined to continue overharvesting unless external solutions were imposed on them. The solutions to be imposed were frequently presented as "the only way" to reduce externalities and increase efficiency. One proposed solution was control of natural resources by a central government agency. The second favored solution was the imposition of private property. Something had to be wrong with the theories, the interpretation of the theories, or the policy prescriptions if solutions as different as state control and market control were both proposed as the only way to manage natural resources efficiently.

By clarifying terms and conducting careful empirical research, researchers have identified a wide diversity of institutional arrangements that individuals have used to overcome tragedy of the commons scenarios. The dominant theories of a decade ago have not been proved wrong; rather, their claim to universal applicability has been successfully challenged. Both experimental and field research readily establishes that when those using resources whose legal status is open access are constrained by diverse factors to act independently, the predictions derived from the "tragedy of the commons" (31), the Prisoners' Dilemma game (32), and the logic of collective action (55; see also 68) are empirically supported (41, 60). Where valued resources are left to be open access, one can expect conflict, overuse, and the potential of destruction.

Common-Pool Resources

Scientific progress is made across the biological and social sciences when crucial attributes are identified that generate predictions about the behavior of the objects under study. Entities that share these crucial attributes differ in other respects that may also be important in providing a full explanation of system behavior. For social scientists interested in questions of resource governance and management, two attributes of resources are the first to be identified in efforts to understand how institutions interact with resources to produce incentives leading toward destruction or sustainability of a resource system. These attributes are 1) the *difficulty of exclusion*, and 2) the *subtractability of benefits* consumed by one person from those available to others (60).

EXCLUSION The goods and events that individuals value differ in terms of how easy or costly it is to exclude or limit potential beneficiaries (users) from consuming them once they are provided by nature or through the activities of other individuals. Fencing and packaging are physical means of excluding potential beneficiaries from goods. To be effective, however, fencing and packaging must be backed by property rights that are feasible to defend (in an economic and legal sense). It follows that the feasibility of excluding or limiting use by potential beneficiaries is derived both from the physical attributes of the goods and from the institutions used in a particular jurisdiction (60).

Excluding or limiting potential beneficiaries from using a common-pool resource is a nontrivial problem for many reasons. In some cases, the problem is the sheer size of a resource. For example, the total cost of "fencing" an inshore fishery, let alone an entire ocean, is prohibitive. In other cases, the additional benefits from exclusion, or placing restrictions on use, are calculated to be less than the additional costs from instituting a mechanism to control use. In still other cases, basic constitutional or legal considerations prevent exclusion or limiting use (60). Knowing that a resource is one that is difficult to exclude, one can predict that "free riding" behavior will occur. *Free riding* is a term used to describe situations where some individuals "free ride" on the efforts of other individuals to provide either the good itself or the set of rules (and their monitoring and enforcement) that would enable individuals to achieve a sustainable, long-term utilization pattern in relationship to a resource (55, 68).

SUBTRACTABILITY The goods and events that individuals value also differ in terms of the degree of subtractability of one person's use from that available to be used by others. If one fisherman lands a ton of fish, that ton is not available for others. On the other hand, one person's enjoyment of a sunset does not subtract from others' enjoyment of a sunset. Information is the extreme case of a good that is not subtractable. Most natural resources, on the other hand, are characterized by subtractable uses.

Goods characterized by problems of exclusion without any subtractability are considered to be public goods (60, 68). Institutions well-adapted for providing public goods are unlikely to solve the overharvesting and potential destruction problems faced in coping with common-pool resources characterized by problems of exclusion and subtractability. Common-pool resources include both natural resources and artifactual facilities designed by humans. Besides sharing two attributes in common, this broad set of resource systems differs on many other attributes.

A common-pool resource creates the conditions for the existence of a stock that may be quantified in terms of resource units. This stock may be the source of one or more flows of resource units over time. Examples of common-pool resources and their resource units include: 1) a groundwater basin and acre-feet of water, 2) a fishing ground and tons of fish, 3) an oil field and barrels of oil, 4) computer facilities and processing time, and 5) parking garages and parking spaces. It is the resource units that are subtractable from a resource. The fish (oil, water) being harvested are a flow, appropriated from a stock of fish (oil, water) (60).

The distinction between the resource stock and the flow of resource units is especially useful in connection with renewable resources that are predictable enough so that one can define a regeneration rate. As long as the rate of appropriation of resource units from a common-pool resource does not exceed the regeneration rate, the resource stock will not be exhausted. When a resource has no natural regeneration (an exhaustible resource), then any appropriation rate will eventually lead to exhaustion.

Subtractability and difficulties of excluding beneficiaries help identify two of the core problems anyone trying to develop institutions leading to sustainability must solve. First, the boundaries that define or include individuals who are authorized to access, harvest, manage, exclude, or sell rights to the use of a resource need to be well-defined (see 71). Second, rules allocating harvesting rights and duties must be devised to keep total use within the bounds of sustainable use. Subtractability and exclusion are not, however, all of the important attributes that affect problems of designing institutions to sustain a resource.

OTHER ATTRIBUTES OF COMMON-POOL RESOURCES The challenge of devising workable rules, however, is also affected by other attributes that differentiate among types of common-pool resources. Schlager et al (70), for example, discuss the importance of the degree of mobility of resource units and the presence or absence of storage. Mobility refers to the spatial movement of resource units, such as flowing water or migratory fish. Water in a lake, or lobsters, are relatively stationary when contrasted to water in a river, or salmon. Storage refers to the capacity to store and retain harvested units. The amount of storage in an irrigation system is close to zero on most run-of-the-river irrigation systems, but it can be extremely high in a conjunctive use system, depending on groundwater basins for storage or a large surface irrigation system with many dams along the course. Schlager et al (70) illustrate how these attributes affect the severity of the problems resource users face, the ease with which they can solve problems, and the type of institutional arrangements most frequently used to solve these problems. The effects of mobility and storage are due to the impact of these physical attributes on:

1. the information users have about their common-pool resources and the problems they are experiencing;
2. the likelihood that users will be able to capture the benefits that issue from their efforts to solve problems; and
3. their assurance about the behavior of other users (70, p. 297).

Whether the resource units must be used within a resource system or are exportable also affects the incentives of users and the problems of regulation. Fish and water can be exported. Once resource units are removed from a common-pool resource, they are similar to other private goods, but their marketability may be one of the incentives that leads to overharvesting. Parking space and computer processing time must be used by multiple individuals within the same entity. Resource units that must be used in a shared facility can be affected by the time and type of use of the other units being used simultaneously and sequentially. Other attributes, such as the asymmetry of interests among participants, are also important (81).

Whether the common-pool resource is physical or biological also makes a considerable difference in the ability of institutions to use and care for a resource sustainably. Institutions adapted for single product physical resources have an easier allocation problem to solve than the set of allocation rules required for the sustained use of biological resources, especially multispecies ones like fisheries or diverse tropical forest ecosystems. Compared to the sharing of a physical resource, the appropriation of complex biological resources has many more ecological variables influencing what resources can be used, when they can be used, and to what extent they may be extracted, while still maintaining the integrity of the resource base. Complex biological resources typically have more uncertainty associated with them than do single physical resources. According to Mayr (46), emergence, the origination of unsuspected qualities or properties at higher levels of integration in complex hierarchical systems, is vastly more important in living than in inanimate systems. We discuss this in more detail later.

DESIGN PRINCIPLES AND ROBUST INSTITUTIONS

As part of an extended effort to study common-pool resources and the institutional arrangements that enhance the capacity of individuals to use these resources in a sustainable way over long periods of time, we have identified a diversity of common-pool resources and related institutions that have been used intensively by humans (56, 59, 60, 90, 91). These institutions are considered to be robust in the sense that both the resource systems and the institutions have survived for long periods of time. The day-to-day operational rules of these systems have undergone change, but these changes have occurred within a set of collective-choice and constitutional-choice rules (75). Some of the robust systems that have been studied in some detail include those of the Swiss Alpine meadows (26, 27, 53); Japanese mountain areas (48); 1000-year-old Spanish irrigation systems (28, 42); California groundwater basins (12); and indigenous irrigation systems in the Philippines (78).

Robust institutions tend to be characterized by most of the design principles listed in Table 1. Clearly defining the boundaries (Principle 1) helps to identify who should receive benefits and pay costs. Equating benefits and costs (Principle 2) is considered a fair procedure in most social systems. Decisions by local users to establish harvesting and protection rules (Principle 3) enable those with the most information and stake in a system to have a major voice in regulating use. The first three principles together help solve core problems associated with free riding and subtractability of use. Rules made to solve these problems are not, however, self-enforcing. Thus, monitoring (Principle 4), graduated sanctioning (Principle 5), and conflict-resolution mechanisms (Principle 6) provide ongoing mechanisms for invoking and interpreting rules and finding ways of assigning sanctions that increase common knowledge and agreement. Recognizing the formal rights of users to do the above (Principle 7) prevents those who want to evade local systems from claiming a lack of

Table 1 Design principles derived from studies of long-enduring institutions for governing sustainable resources

1. *Clearly Defined Boundaries*
   The boundaries of the resource system (e.g. groundwater basin or forest) and the individuals or households with rights to harvest resource products are clearly defined.
2. *Proportional Equivalence Between Benefits and Costs*
   Rules specifying the amount of resource products that a user is allocated are related to local conditions and to rules requiring labor, materials, and/or money inputs.
3. *Collective-Choice Arrangements*
   Most individuals affected by harvesting and protection rules are included in the group who can modify these rules.
4. *Monitoring*
   Monitors, who actively audit physical conditions and user behavior, are at least partially accountable to the users and/or are the users themselves.
5. *Graduated Sanctions*
   Users who violate rules are likely to receive graduated sanctions (depending on the seriousness and context of the offense) from other users, from officials accountable to these users, or from both.
6. *Conflict-Resolution Mechanisms*
   Users and their officials have rapid access to low-cost, local arenas to resolve conflict among users or between users and officials.
7. *Minimal Recognition of Rights to Organize*
   The rights of users to devise their own institutions are not challenged by external governmental authorities, and users have long-term tenure rights to the resource.

For resources that are parts of larger systems:

8. *Nested Enterprises*
   Appropriation, provision, monitoring, enforcement, conflict resolution, and governance activities are organized in multiple layers of nested enterprises.

Source: Ostrom (56, p. 90).

legitimacy. In addition, nesting a set of local institutions into a broader network of medium- to larger-scale institutions helps to ensure that larger-scale problems are addressed as well as those that are smaller. Institutions that have failed to sustain resources tend to be characterized by very few of these design principles, and those that are characterized by some, but not most, of the principles are fragile.

The design principles are articulated in Table 1 in a general language. The specific ways that individual users have crafted rules to meet these principles vary. Successful, long-enduring irrigation institutions, for example, have developed different ways of meeting the second design principle of achieving congruence or proportionality between the costs of building and maintaining irrigation systems and the distribution of benefits. Three examples below illustrate the diversity of specific rules that meet the second design principle.

The *zanjeras* of Northern Philippines are self-organized systems in which farmers obtain use-rights to previously unirrigated land from a large landowner by building a canal that irrigates the landowner's land and that of a *zanjera.* At the time of land allocation, each farmer who agrees to abide by the rules of the system receives a bundle of rights and duties in the form of *atars*. Each *atar* defines three parcels of land located in the head, middle, and tail sections of the service area where the holder grows his or her crops. Responsibilities for construction and maintenance are allocated by *atars*, as are voting rights. In the rainy seasons, water is allocated freely. In a dry year, water may be allocated only to the parcels located in the head and middle portions. Thus, everyone receives water in plentiful and scarce times in rough proportion to the amount of *atars* they possess. *Atars* may be sold to others with the permission of the irrigation association, and they are inheritable (see 18, 78, 84).

When the *Thulo Kulo* irrigation system was first constructed in 1928, 27 households contributed to a fund to construct the canal and received shares proportionate to the amount they invested. Since then, the system has been expanded by selling additional shares. Measurement and diversion weirs or gates are installed at key locations so that water is automatically allocated to each farmer according to the proportion of shares owned. Routine monitoring and maintenance is allocated to work teams so that everyone participates in proportion to their share ownership, but emergency repairs require labor input from all shareholders regardless of the size of their share (see 43, 44). Similar self-organized systems exist throughout Nepal (37, 61, 67, 76, 93, 94).

In 1435, 84 irrigators served by two interrelated canals in Valençia gathered at the monastery of St. Francis to draw up and approve formal regulations to specify who had rights to water from these canals, how the water would be shared in good and bad years, and how responsibilities for maintenance would be shared. The modern *Huerta* of Valençia, composed of these plus six additional canals, now serves about 16,000 ha and 15,000 farmers. The right to water inheres in the land itself and cannot be bought and sold independently of the land. Rights to water are approximately proportionate to the amount of land, as are obligations to contribute to the cost of monitoring and maintenance activities (see 42).

Five hundred years after the irrigators of Valençia devised a system to allocate water rights, modern water users dependent upon the groundwater basins underlying Los Angeles County also started meeting to discuss how to allocate water rights among municipal, industrial, and agricultural users (12, 56). They all faced the potential destruction of their valuable groundwater basins if they continued the pumping race that unsettled property rights had encouraged during the prior decades. Over a 40-year period, groundwater pumpers in four adjacent basins established private water associations that invested heavily in obtaining accurate information about the geologic and hydrologic characteristics of the basins. Further, water producers bargained in the shadow of equity courts to define water shares based on historical use patterns and to develop proportionate reductions in authorized, annual water withdrawals. The costs of monitoring these systems over time and enforcing the agreements are paid for by water users in proportion to the amount of water they produce. Participants also established limited, special-purpose water districts to manage other aspects of the groundwater basins not covered by limiting the quantity of withdrawals. The institutional arrangements developed by water users meet all eight of the design principles listed in Table 1 (56, p. 180). Several of these agreements have now been in practice for half a decade and show no signs of losing their overall effectiveness in protecting the sustainability of the groundwater basins over time.

These four systems differ substantially. The *zanjeras* are ways landless laborers can acquire use-rights to land and water. These could be called communal systems. The *Thulo Kulo* system comes as close to allocating private and separable property rights to water as is feasible in an irrigation system. This might be called a private or market solution. The *Huerta* of Valençia has maintained centuries-old land and water rights that forbid the separation of water rights from the land being served. The Valençian system differs from both "communal" and "private property" systems because water rights are firmly attached to ownership of land. The California groundwater systems privatized water rights (the flow), and a vigorous market for these water rights ensued. At the same time, limited-purpose, public, local jurisdictions assumed responsibility for managing the basins (the resource system or stock) by assessing pump taxes and undertaking replenishment programs. Underlying these strong differences, however, is the basic design principle that the costs of constructing, operating, and maintaining these systems are roughly proportional to the benefits that participants obtain. Since those who are users of these systems have devised their rules over time using trial and error methods, one should not presume that there was a conscious overall plan to develop institutions that met the design principles. Rather, the design principles are an effort of careful observers to identify commonalities that help to account for sustainability of fragile resources over very long periods of time.

Differences like the ones illustrated here lead us to stress the importance of design principles rather than specific institutional solutions to common-pool resource problems. The contribution of social and biological scientists to the study of sustainable resource systems can be substantial if general theoretical principles are identified rather than searching for particular institutional solutions that are prescribed as universal solutions. Universal solutions can tend to become slogans, such as "nature reserves," "privatization," "individual transferable quotas," "integrated rural development projects," and "joint management schemes." There are successful and unsuccessful examples of all of these types of programs that differ from one another in important institutional and ecological variables.

Slogans may mask important underlying principles involved in many of the successful efforts to utilize individual transferable quotas or joint management schemes rather than providing useful guides for reform. Strict privatization of water rights is not a feasible option within the broad institutional framework of many countries. Nor is it easy to see how one can accomplish this in a run-of-the-river system. The only institutional arrangements that we know where water users own strict quantitative shares to water are those involving storage—either groundwater or constructed surface storage. Even in groundwater basins, one can privatize the flow of the resource (once good scientific information is available about long-term climate, geologic, and hydrological characteristics). But the basin itself cannot be parcelled out and must be used jointly. Nor can a dam be parcelled out—especially one that generates hydroelectric power, recreation, and flood control benefits in addition to water supply. Thus, flow characteristics may be allocated in a different way than stock and facility characteristics. On the other hand, authorizing the beneficiaries of a common-pool resource to participate in the design of their own systems—design principles 3 and 7 combined—is a feasible reform within the broad institutional framework of most countries and most ecological settings.

FACTORS AFFECTING INSTITUTIONAL VARIETY

Not only is a substantial variety of rules used to reduce the cost of externalities from unregulated use of natural resources, but neighboring systems that appear to face similar situations frequently adopt different solutions. Within a few miles of Valençia is Alicante, where irrigators long ago built a surface dam and adopted rules separating water from the land. The weekly water market in Alicante has operated for centuries. Adjacent to *Thulo Kulo* is *Raj Kulo,* where the allocation of water (and labor responsibilities) is according to the amount of land owned. Near the *zanjeras* are many irrigation systems with quite different rules for distributing water and input responsibilities. Near the water basins in Los Angeles County are basins in Orange, San Bernardino, and Riverside Counties where pumpers have refused to undertake litigation to clarify their water rights (12).

The variety of rules selected by local users who appear to face similar circumstances raises the question of whether the choice of institutional arrangements is an evolutionary process involving selection for more efficient institutions over time. In an important article, Alchian (2) demonstrated how the pressure of competitive markets would select surviving firms that used profit-maximizing strategies whether they had chosen these strategies self-consciously or not. Some advocates of market orders (72, 83, 88) have argued that individuals will slowly establish new and more efficient institutions through a series of spontaneous individual decisions. The improved group outcome is conceptualized as an unintended result of individual learning and adjusting behavior over time. It is not quite clear, however, what selection principle is at work outside of competitive markets.

Others, including Knight (35) and Ostrom (56, 58), point out that changes in rules usually occur within a meta set of rules at a collective choice or constitutional level and within settings that vary in terms of pressure for survival or excellence. The meta set of rules may assign different advantages to various participants in the rule-changing process. Those with the most voice in collective-choice processes may refuse to support a change if they do not benefit themselves from the change in rules. This can occur even when the aggregate benefit of a rule change is large. Thus, to explain a change in rules, one needs to analyze not only the status quo distribution of costs and benefits but also the distributional effects of proposed rules (40) and how these relate to the meta rules used for making and changing rules.

To explain institutional change, one needs to analyze the relationships between variables characterizing the resource, the community of individuals involved, and the meta rules for making and changing rules. Sufficient theoretical and empirical research has been conducted on this and the closely related theory of collective action to enable one to specify important variables and the direction of their impact. The following variables appear to be conducive to the selection of norms, rules, and property rights that reduce externalities (6, 7, 19, 38–40, 48, 49, 56):

1. Accurate information about the condition of the resource and expected flow of benefits and costs are available at low cost.
2. Participants are relatively homogeneous in regard to asset structure, information, and preferences.

3. Participants share a common understanding about the potential benefits and risks associated with the continuance of the status quo as contrasted with changes in norms and rules that they could feasibly adopt.

4. Participants share generalized norms of reciprocity and trust that can be used as initial social capital.

5. The group using the resource is relatively small and stable.

6. Participants do not discount the future at a high rate.

7. Participants have the autonomy to make many of their own operational rules, which if made legitimately, will be supported and potentially enforced by external authorities.

8. Participants use collective-choice rules that fall between the extremes of unanimity or control by a few (or even bare majority), and thus they avoid high transaction or high deprivation costs.

9. Participants can develop relatively accurate and low-cost monitoring and sanctioning arrangements.

Many of these variables are, in turn, affected by the type of larger regime in which users are embedded. If the larger regime facilitates local self-organization by providing accurate information about natural resource systems, providing arenas in which participants can engage in discovery and conflict-resolution processes, and providing mechanisms to back up local monitoring and sanctioning efforts, the probability of participants adopting more effective rules over time is higher than in regimes that ignore resource problems or presume that all decisions about governance and management need to be made by central authorities.

THE CHALLENGES OF COMMON-POOL BIOLOGICAL RESOURCES

Biological resources, both single species and multispecies systems, have a set of uncertainties that stem from being part of an interacting community of organisms. A physical resource like water may have many competing uses, but whether a replenishable amount is used in farming or municipal water supply does not affect the long-term sustainability of the resource. In contrast, the harvest of individuals from living populations in terrestrial or aquatic ecosystems can affect the future availability of both the particular species and others with which it interacts. For example, a community timber-harvesting program that is modeled to be sustainable could eliminate the sustainable harvest of medicinal herbs in a forest by altering the sunlight and moisture in the understory. The ecological and economic trade-offs associated with multispecies systems are extremely complex and thus require long-term trial-and-error social experiments to arrive at optimal, or even feasible, use patterns

(20). Imposing rigid private property or central authority on a multispecies resource use system that has evolved over centuries may not only adversely affect the very human groups who have been responsible for successfully husbanding resources but may also adversely affect the ecological function of the resource systems (11, 22, 24, 25).

One principle that today is grossly inappropriate for complex systems, but still guides allocation of biological resources, is the concept of maximum sustained yield (MSY). This is not to say that we should completely abandon attempts to manage some single-species resources at MSY, but the concept fails in most dynamic systems. Plant and animal populations that have very predictable regenerative properties within a complex community can be managed in a sustained-yield fashion, but they are more an exception than the rule. A greater number of species have chaotic population patterns (92). When recruitment and yield are predictable, allocation rules and institutions may be fairly simple, understandable, and trusted by users. For example, the plaice fishery in the North Sea has a long history of MSY, and it has a predictable stock-recruitment pattern, showing only a six-fold variation during three decades (9). In contrast, the North Sea haddock varies by 500-fold in its abundance at recruitment and has recently been overfished to the point of requiring closure of the fishery (36).

Setting the MSY of a living resource is challenging because environmental conditions fluctuate, causing values of MSY to fluctuate. Climatic, demographic, and environmental stochasticity can greatly alter the sustainability of a set of species being managed at MSY. On a closed system, mixed-species game ranch in Kenya, when predators were reduced, the number of wildebeests, Thomson's gazelles, Grant's gazelles, and hartebeests increased. Sex ratios were purposely skewed toward females to increase productivity, and the populations were culled in a sustainable proportion to their reproductive potential. Conservative but complex biological models were employed to select the animals for culling. For a few years, the system produced an economically profitable and biologically sustainable supply of meat to specialty markets in Nairobi. However, the ecological sustainability of the closed system collapsed during a drought in 1984, when ungulate numbers and diversity plummeted, requiring managers to open the system to acquire more stock to keep the business going (82). Getting the biology right is not easy!

To complicate matters further, misinterpretation of economic models and self-interest have favored overexploitation of many common-pool resources, especially fisheries. For decades, and probably still for some today, there has been a misconceived notion that maximum economic yield (total revenue minus total cost) usually falls below MSY (30). Clark (17) showed that discounting the future (the preference to make one dollar today rather than two dollars in the future) encourages fishing far beyond MSY under many reasonable conditions. Many current-day institutions encourage users to discount the future, strongly leading to strategies that are neither ecologically nor economically sustainable.

Societies driven to the efficiency level that favors overcapitalization and large corporate exploitation have failed to use diverse biological resources sustainably, largely because resource developers have banked on substitutability for sustainability. So long as any species of sea organism will do for a commodity such as "fish meal," or so long as natural capital can be reinvested in any form of capital, biological resources can be, by definition, economically sustaining (80; but see 33). Trees can be cut and sold, made into pulp and paper, and earnings may be reinvested in other sectors. From this perspective, economic sustainability is operationally defined as exploiting nature's capital whenever it is efficient to do so, and switching to other forms of capital when nature's value drops below some threshold. Substitution as currently practiced has serious ecological limits, because eventually all the components get used up. If the switches among resources were made within the realm of biological capital only, and with the goal of sustaining each resource in the pool of potential commodities, we would stand a better chance of sustaining all of the resources. Each form of natural capital (species) is sustainable only when its use is equal to its replenishment as dictated by interactions with other species and disturbance regimes that affect the system.

To achieve ecologically sustainable use of diverse biological resources, either we need reliable models that adequately predict complex demographics, effects of species interactions, and disturbance stochasticity, or we need to be very conservative in our exploitation of any one resource in the array. In practice, the latter approach is the more attainable, but it is certainly not the current paradigm in commercial resource management.

Human societies with a long history of interdependence with multispecies resources should evolve institutions that optimize the turnover and use of extractables without compromising the functional aspects of the ecosystem or the future availability of important products (8). In other words, their rule systems should maintain the diversity that sustains the multitude of useful species. What sort of social arrangements would do this? Opportunistic substitution would be sustainable at low human densities, so until the resources were scarce, one would predict little in the way of restraints on use. Excavations of ancient food middens of native people living on the Aleutian Islands indicate that exploitation of certain species in the Pacific kelp bed ecosystem caused the biological community to flip back and forth between two major equilibria. There were periods when sea otter bones and fish dominated the middens, and periods when mainly sea urchin skeletons dominated the refuse piles (77).

Under conditions where diverse and scarce resources are in demand (consumptively or nonconsumptively), one would predict institutions with some form of strict protection of the habitat that supports the scarce biota. Sacred forests in Africa (29) and Shaman's gardens in Amazonia (66) have been interpreted as institutionalized insurance against overexploitation of rare biological resources, especially medicinal or ceremonial species. Natural area protection at local, national, and international scales indicates widespread attempts to buffer biological resources from overutilization (15).

Rules that favor the use of a little bit of everything, but overutilization of nothing, would be expected along with complex social systems for resource allocation and monitoring. In the modern-day Mayan community of Chunhuhub in the forests of Quintana Roo, Mexico, people still speak of "Yuntzilob," the forest deities who bring disaster on those who overuse biological resources. According to Anderson (3), many of the well-educated youth of this community today see the ecological importance of these beliefs.

Subsistence societies around the world have evolved institutions that sustain themselves and the complex biological natural resources upon which they depend for survival (66). In the Amazon, Tukano Indians living along the blackwater tributaries have strict rules against deforestation along the river margins. These riparian areas are reserved for the feeding grounds of fish. The ecological basis of this rule becomes apparent in the relative lack of fish in flooded areas that have been deforested (16), and in the poor agricultural yields on the low-nutrient blackwater flood plains. The relatively high dietary protein levels and population densities of the Tukano also support the idea that the rule against deforestation has a direct advantage to the individual rule makers in terms of Darwinian fitness.

Throughout Amazonia, Amerindians practice a form of agriculture that is considered to be benign in terms of ecosystem functions such as nutrient cycling, depletion of species, and gas exchange (87). Many Amerindians maintain small, species-diverse garden plots of less than an acre, similar in size to a natural gap produced by treefall. They combine perennial tree crops with natural forest regeneration in their method of swidden cultivation (21). Their fallow swiddens are often more species rich than the mature forest. Semi-nomadic Kayapo Indians in Brazil take edible tubers, fruit trees, and medicinal plants from the forest interior and plant them along their trails and adjacent to their campsites, thus changing the distributions of useful resources, without depleting original stocks (65).

Currently, the ecologically sustainable systems of traditional societies are in direct conflict with the dominant product orientation of global-market enterprises such as livestock ranching, timber harvesting, and monoculture farming (50, 51, 79). The sustainability of complex multispecies resource systems is also endangered by the decay of the indigenous taboos and rules that were so adaptive in the first place (4). Population growth has put a strain on traditional institutions. With more people demanding land, some modern Mayan communities have modified traditional rules for fallow periods, shortening them to allow more families the opportunity to farm (3). People can self-organize on a local level to maintain complex biological systems, but they must have a long-term, adaptive relationship with the resources to do so.

CURRENT RESEARCH ON HUMAN INSTITUTIONS AND FOREST ECOLOGY

Future research will need to include theoretical and empirical studies that specifically address how heterogeneity of participants, multispecies or multiproduct resource systems, and long time horizons affect the selection and performance of institutions. We are currently developing a theoretical and empirical program of research—the International Forestry Resources and Institutions (IFRI) research program (see 62). The IFRI research program combines an effort to examine how diverse institutional arrangements perform within similar and across different ecological zones with an effort to monitor and understand human-ecological systems interactions over long periods of time. The theoretical questions relate in part to whether the design principles derived from studying robust institutions of smaller and somewhat simpler common-pool resources (see Table 1) are applicable in designing institutions to sustain complex forest ecologies. Further, an important set of questions relate to the conditions under which local communities will overcome severe collective-action problems to design, monitor, and enforce their own local institutions and how well diverse types of local, regional, and national institutions will perform in different types of forest ecologies (see 49).

Our current research program is now beginning a long-term operational phase after a two-year design, pretest, and pilot phase. Three collaborating research centers in Bolivia, Nepal, and Uganda have been established, and initial research has also been undertaken in India. In an IFRI study of two adjacent and similar-sized parcels of forested land in Uganda, institutions explained major differences in the physical and biological condition of the forest. Namungo forest was family-owned, was well-monitored, and had clear rule structures. Collective and individual action by local forest consumers could be used to negotiate and modify rules for exploitation of many subsistence products in Namungo's forest. Commercial use of Namungo forest was forbidden, and sanctions were clear. In contrast, Lwamunda forest, as public property, was poorly monitored, lacked any rules negotiated by local users, had unclear boundaries, and had poorly specified sanctions. Based on the design principles discussed above (Table 1), Lwamunda was expected to show more "open-access" utilization and more degradation than Namungo forest. In 30 random plots of 300 m^2 made in each forest, plots degraded by timber milling, charcoal-making, and commercial exploitation of fuelwood were significantly more prevalent in Lwamunda than in Namungo forest. A different set of tree species dominated each forest area, the depleted species clearly reflecting recent utilization preferences (5). Rules and their effectiveness at the local level are critical to the sustainability of complex biological resources.

Initial findings from an in-depth study of five forests in the Almora district of the Kumaon region of Uttar Pradesh in India indicate that the expected strong relationship between population density (number of people per hectare of forest) and lower forest density (cubic meters of tree biomass per hectare) is not present in the first five self-organized communities sampled in this region (1). Further, Agrawal finds that somewhat larger communities are better able to raise the needed resources to hire forest guards to monitor the use of communal forests. Thus, the presumption in collective-action theory that very small communities are better able to overcome collective-action problems may not hold when the type of collective action required involves the mobilization of substantial resources.

CONCLUSION

Now that nature's capital including water, old-growth forests, and fishery stocks is becoming scarcer relative to growing stocks of human-made capital, investments in protecting nature's capital and the efficiency of its use are becoming more central to long-term economic sustainability. To achieve long-term economic sustainability, we need more than ever before a combination of institutions that restrain shortsighted and selfish behavior and that make rules based on flexible and cautious models of the ecology of complex biological systems. We are entering an age when we need to reduce our losses of natural capital, and one substitution after another is no longer a risk we can afford to take. Flipping from complex equilibria to simpler ones to eke out sufficient food in the short run will produce long-run scarcities of essential biological resources. Coevolution via cautious trial-and-error exploitation is a better strategy than use of rigid MSY models for setting harvest levels of multispecies resources. Extinction roulette with poor management of multispecies resources is not a prudent strategy for the twenty-first century.

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Political Theory and Policy Analysis. Ostrom is the Arthur F. Bentley Professor of Political Science and the Co-Director of the Workshop in Political Theory and Policy Analysis.

Literature Cited

1. Agrawal A. 1994. *Small is beautiful, but could larger be better? A comparative analysis of five village forest institutions in the Indian Middle Himalayas.* Presented at 1st Annu. Meet. Int. For. Resourc. Inst. Network, Oxford For. Inst., Oxford, India, Dec. 15–18
2. Alchian A. 1950. Uncertainty, evolution, and economic theory. *J. Polit. Econ.* 58:211–21
3. Anderson EN. 1992. *Can Ejidos work? Forest management in a Maya community.* Presented at Int. Assoc. for the Study of Common Property Meet., Washington, DC, Sept.
4. Atran S. 1993. Itza Maya tropical agroforestry. *Curr. Anthropol.* 34(5):633–700
5. Becker CD, Banana A, Gombya-Ssembajjwe W. Early detection of tropical forest degradation: an IFRI pilot study in Uganda. *Environ. Conserv.* *Forthcoming*
6. Benjamin P, Lam WF, Ostrom E, Shivakoti G. 1994. *Institutions, Incentives, and Irrigation in Nepal. Decentralization: Finance & Management Project Report.* Burlington, VT: Assoc. in Rural Dev.
7. Berkes F, ed. 1989. *Common Property Resources: Ecology and Community-based Sustainable Development.* London: Belhaven
8. Berkes F, Folke C. 1994. *Linking social and ecological systems for resilience and sustainability.* Presented at Worksh. on Property Rights and the Performance of Natural Resource Systems, Swedish Acad. Sci., Beijer Intl. Inst. of Ecological Econ., Stockholm
9. Beverton RJH. 1962. Long-term dynamics of certain North Sea fish populations. In *The Exploration of Natural Animal Populations,* ed. ED LeCren, MW Holdgate, pp. 242–59. Oxford: Blackwell
10. Blaikie PM, Brookfield H. 1987. *Land Degradation and Society.* London: Methuen
11. Blewett RA. 1994. *Property rights as a cause of the tragedy of the commons: institutional change and the pastoral Maasai in Kenya.* Presented at Public Choice Soc. Meet., Austin, Texas, April 8–10
12. Blomquist W. 1992. *Dividing the Waters: Governing Groundwater in Southern California.* San Francisco: ICS
13. Bromley DW. 1991. *Environment and Economy: Property Rights and Public Policy.* Oxford: Blackwell
14. Bromley DW, Feeny D, McKean M, Peters P, Gilles J, et al., eds. 1992. *Making the Commons Work: Theory, Practice, and Policy.* San Francisco: ICS
15. Castañeda J. 1992. Union of forest Ejidos and communities of Oaxaca. In *Development or Destruction: The Conversion of Tropical Forest to Pasture in Latin America,* ed. TE Downing, SB Hecht, HA Pearson, and C Garcia-Downing, pp. 333–34. Boulder, CO: Westview
16. Chernela JM. 1989. Managing rivers of hunger: the Tukano of Brazil. *Adv. Econ. Bot.* 7:238–48
17. Clark CW. 1990. *Mathematical Bioeconomics: The Optimal Management of Renewable Resources.* New York: Wiley
18. Coward EW, Jr. 1979. Principles of social organization in an indigenous irrigation system. *Hum. Organ.* 38(1):28–36
19. Curtis D. 1991. *Beyond Government: Organizations for Common Benefit.* London: Macmillan
20. Dove MR. 1993. A revisionist view of tropical deforestation and development. *Environ. Conserv.* 20:17–24
21. Dufour DL. 1990. Use of tropical rainforests by native Amazonians. *BioScience* 40(9):652–59
22. Folke C, Holling CS, Perrings C. 1994.

Biodiversity, ecosystems and human welfare. Work. Pap. No. 49. Stockholm: Swedish Acad. Sci., Beijer Intl. Inst. Ecological Econ.
23. Fortmann L, Bruce JW, eds. 1988. *Whose Trees? Proprietary Dimensions of Forestry.* Boulder, CO: Westview
24. Gadgil M, Berkes F, Folke C. 1993. Indigenous knowledge for biodiversity conservation. *Ambio* 22(2-3):151–56
25. Gadgil M, Rao PRS. 1994. *On designing a system of positive incentives to conserve biodiversity for the ecosystem people of India.* Presented at Worksh. on Design Principles, Swedish Acad. Sci., Beijer Int. Inst. Ecol. Econ., Stockholm
26. Glaser [Picht] C. 1987. *Common property regimes in Swiss alpine meadows.* Presented at Conf. on Advances in Compar. Institutional Anal., Inter–University Ctr. of Postgrad. Stud., Dubrovnik, Yugoslavia
27. Glaser [Picht] C. 1987. *Field notes to CPR colleagues.* Bloomington: Indiana Univ., Worksh. in Polit. Theory & Policy Anal.
28. Glick TF. 1970. *Irrigation and Society in Medieval Valencia.* Cambridge, MA: Harvard Univ. Press, Belknap Press
29. Gombya-Ssembajjwe W. 1994. *Sacred forests in modern Ganda society.* Presented at FAO For. Work. Group Meet. on Common Property, Oxford For. Inst., Oxford, UK, Dec. 15–18
30. Gordon HS. 1954. The economic theory of a common property resource: the fishery. *J. Polit. Econ.* 62:124–42
31. Hardin G. 1968. The tragedy of the commons. *Science* 162:1243–48
32. Hardin R. 1982. *Collective Action.* Baltimore, MD: Johns Hopkins Univ. Press
33. Jansson A, Hammer M, Folke C, Costanza R. 1994. *Investing in Natural Capital.* Washington, DC: Island
34. Keohane RO, Ostrom E, eds. 1995. *Local Commons and Global Interdependence: Heterogeneity and Cooperation in Two Domains.* London: Sage
35. Knight J. 1992. *Institutions and Social Conflict.* Cambridge, MA: Cambridge Univ. Press
36. Krebs CJ. 1994. *Ecology.* New York: Harper Collins. 4th ed.
37. Laitos R, et al. 1986. *Rapid Appraisal of Nepal Irrigation Systems. Water Management Synthesis Rep. No. 43.* Fort Collins: Colorado State Univ.
38. Lam WF. 1994. *Institutions, engineering infrastructure, and performance in the governance and management of irrigation systems: the case of Nepal.* PhD thesis. Indiana Univ., Bloomington
39. Lee M. 1994. *Institutional analysis, public policy, and the possibility of collective action in common pool resources: a dynamic game theoretic approach.* PhD thesis. Indiana Univ., Bloomington
40. Libecap GD. 1989. *Contracting for Property Rights.* Cambridge, MA: Cambridge Univ. Press
41. Libecap GD. 1995. The conditions for successful collective action. In *Local Commons and Global Interdependence: Heterogeneity and Cooperation in Two Domains,* ed. R Keohane, E Ostrom, pp. 161–90. London: Sage
42. Maass A, Anderson RL. 1986. *...and the Desert Shall Rejoice: Conflict, Growth and Justice in Arid Environments.* Malabar, FL: RE Krieger
43. Martin EG. 1986. *Resource mobilization, water allocation, and farmer organization in hill irrigation systems in Nepal.* PhD thesis. Cornell Univ.
44. Martin EG, Yoder R. 1983. The Chherlung Thulo Kulo: a case study of a farmer-managed irrigation system. In *Water Management in Nepal: Proceedings of the Seminar on Water Management Issues,* July 31–Aug. 2, Appendix I, 203–17. Kathmandu, Nepal: Ministry of Agric., Agric. Projects Serv. Ctr., Agric. Dev. Council
45. Martin F. 1989/1992. *Common-Pool Resources and Collective Action: A Bibliography.* Vols. 1 and 2. Bloomington: Indiana Univ., Worksh. in Polit. Theory & Policy Anal.
46. Mayr E. 1982. *The Growth of Biological Thought.* Cambridge, MA: Belknap
47. McCay BJ, Acheson JM. 1987. *The Question of the Commons: The Culture and Ecology of Communal Resources.* Tucson: Univ. Ariz. Press
48. McKean MA. 1992. Management of traditional common lands (Iriaichi) in Japan. In *Making the Commons Work: Theory, Practice, and Policy,* ed. DW Bromley, D Feeny, MA McKean, P Peters, JL Gilles, et al, pp. 63–98. San Francisco: ICS
49. McKean MA, Ostrom E. 1995. Common property regimes in the forest: just a relic from the past? *Unasylva* 46:3–15
50. Moran E. 1983. *The Dilemma of Amazonian Development.* Boulder, CO: Westview
51. Moran E. 1993. *Through Amazonia Eyes: The Human Ecology of Amazonian Populations.* Iowa City: Univ. Iowa Press
52. National Research Council. 1986. *Proceedings of the Conference on Common Property Resource Management.* Washington, DC: Natl. Acad.

53. Netting R McC. 1981. *Balancing on an Alp*. New York: Cambridge Univ. Press
54. Netting R McC. 1993. *Smallholders, Householders: Farm Families and the Ecology of Intensive, Sustainable Agriculture*. Stanford, CA: Stanford Univ. Press
55. Olson M. 1965. *The Logic of Collective Action: Public Goods and the Theory of Groups*. Cambridge, MA: Harvard Univ. Press
56. Ostrom E. 1990. *Governing the Commons: The Evolution of Institutions for Collective Action*. New York: Cambridge Univ. Press
57. Ostrom E. 1992. *Crafting Institutions for Self-Governing Irrigation Systems*. San Francisco: ICS
58. Ostrom E. 1994. Constituting social capital and collective action. *J. Theoret. Polit.* 6(4):527–62
59. Ostrom E, Gardner R, 1993. Coping with asymmetries in the commons: self-governing irrigation systems can work. *J. Econ. Perspect.* 7(4):93–112
60. Ostrom E, Gardner R, Walker J. 1994. *Rules, Games, and Common-Pool Resources*. Ann Arbor: Univ. Mich. Press
61. Ostrom E, Lam WF, Lee M. 1994. The performance of self-governing irrigation systems in Nepal. *Hum. Syst. Manage.* 13(3):197–207
62. Ostrom E, Wertime MB. 1994. *International forestry resources and institutions (IFRI) research strategy*. Work. pap. Bloomington: Indiana Univ., Worksh. in Polit. Theory & Policy Anal.
63. Ostrom V, Feeny D, Picht H, eds. 1993. *Rethinking Institutional Analysis and Development: Issues, Alternatives, and Choices*. San Francisco: ICS. 2nd ed.
64. Pinkerton E. 1989. *Co-operative Management of Local Fisheries: New Directions for Improved Management and Community Development*. Vancouver: Univ. British Columbia Press
65. Posey DA. 1985. Indigenous management of tropical forest ecosystems: the case of the Kayapo Indians of the Brazilian Amazon. *Agrofor. Syst.* 3:139–58
66. Posey DA. 1993. Indigenous knowledge in the conservation of world forests. In *World Forests for the Future,* ed. K Ramakrishna, GM Woodwell, pp. 59–77. New Haven, CT: Yale Univ. Press
67. Pradhan P. 1989. *Increasing Agricultural Production in Nepal: Role of Low-Cost Irrigation Development through Farmer Participation*. Kathmandu, Nepal: Int. Irrigation Manage. Inst.
68. Sandler T. 1992. *Collective Action*. Ann Arbor: Univ. Mich. Press
69. Schlager E. 1994. Fishers' institutional responses to common-pool resource dilemmas. In *Rules, Games, and Common-Pool Resources,* ed. E Ostrom, R Gardner, J Walker, pp. 247–65. Ann Arbor: Univ. Mich. Press
70. Schlager E, Blomquist W, Tang SY. 1994. Mobile flows, storage, and self-organized institutions for governing common-pool resources. *Land Econ.* 70(3):294–317
71. Schlager E, Ostrom E. 1992. Property-rights regimes and natural resources: a conceptual analysis. *Land Econ.* 68(3): 249–62
72. Schotter A. 1981. *The Economic Theory of Social Institutions*. Cambridge, MA: Cambridge Univ. Press
73. Sengupta N. 1991. *Managing Common Property: Irrigation in India and the Philippines*. London: Sage
74. Sengupta N. 1993. *User-Friendly Irrigation Designs*. New Delhi: Sage
75. Shepsle KA. 1989. Studying institutions: some lessons from the rational choice approach. *J. Theoret. Polit.* 1: 131–49
76. Shivakoti GP. 1991. *Organizational effectiveness of user and non-user controlled irrigation systems in Nepal*. PhD thesis. Mich. State Univ., Dep. Resource Dev.
77. Simenstad CA, Estes JA, Kenyon KW. 1978. Aleuts, sea otters, and alternate stable-state communities. *Science* 200: 403–11
78. Siy RY Jr. 1982. *Community Resource Management: Lessons from the Zanjera*. Quezon City: Univ. Philippines Press
79. Skole DL, Chomentowski WH, Salas WA, Nobre AB. 1994. Physical and human dimensions of deforestation in Amazonia. *BioScience* 44(5):314–21
80. Solow R. 1992. *An almost practical step toward sustainability*. Transcript of an invited lecture. Washington, DC: Resources for the Future
81. Sparling EW. 1990. Asymmetry of incentives and information: the problem of watercourse maintenance. In *Social, Economic, and Institutional Issues in Third World Irrigation,* ed. R Sampath, RA Young, pp. 195–213. Boulder, CO: Westview
82. Stelfox JB. 1985. *Mixed species game ranching*. PhD thesis. Univ. Alberta, Edmonton, Alberta, Canada
83. Sugden R. 1986. *The Economics of Rights, Cooperation and Welfare*. London: Basil Blackwell
84. Svendsen M, Small L. 1990. Farmers' perspective on irrigation performance. *Irrigation and Drainage Systems* 4:385–402

85. Tang SY. 1992. *Institutions and Collective Action: Self-Governance in Irrigation.* San Francisco: ICS
86. Thomson JT. 1992. *A Framework for Analyzing Institutional Incentives in Community Forestry.* Rome: Food and Agric. Organ. of the United Nations
87. Uhl C. 1987. Factors controlling succession following slash and burn agriculture in Amazonia. *Ecology* 75: 377–407
88. von Hayek FA. 1967. Notes on the evolution of rules of conduct. In *Studies in Philosophy, Politics, and Economics,* ed. FA von Hayek, pp. 66–81. Chicago: Univ. Chicago Press
89. Wade R. 1988. *Village Republics: Economic Conditions for Collective Action in South India.* New York: Cambridge Univ. Press
90. Weissing F, Ostrom E. 1991. Irrigation institutions and the games irrigators play: rule enforcement without guards. In *Game Equilibrium Models II: Methods, Morals, and Markets,* ed. R Selten, pp. 188–262. Berlin: Springer-Verlag
91. Weissing F, Ostrom E. 1993. Irrigation institutions and the games irrigators play: rule enforcement on government- and farmer-managed systems. In *Games in Hierarchies and Networks: Analytical and Empirical Approaches to the Study of Governance Institutions,* ed. FW Scharpf, pp. 387–428. Frankfurt: Campus Verlag/Boulder, CO: Westview
92. Wilson JA, French J, Kleban P, McKay SR, Townsend R. 1991. Chaotic dynamics in a multiple species fishery: a model of community predation. *Ecol. Modelling* 58:303–22
93. Yoder RD. 1986. *The performance of farmer-managed irrigation systems in the hills of Nepal.* PhD thesis. Cornell Univ.
94. Yoder RD. 1994. *Locally Managed Irrigation Systems.* Columbo: Int. Irrigation Manage. Inst.