# Insights on linking forests, trees, and people from the air, on the ground, and in the laboratory

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**Governing natural resources sustainably is a continuing struggle. Major debates occur over what types of policy ''interventions'' best protect forests, with choices of property and land tenure systems being central issues. Herein, we provide an overview of findings from a long-term interdisciplinary, multiscale, international research program that analyzes the institutional factors affecting forests managed under a variety of tenure arrangements. This program analyzes satellite images, conducts social-ecological measurements on the ground, and tests the impact of structural variables on human decisions in experimental laboratories. Satellite images track the landscape dimensions of forest-cover change within different management regimes over time. On-the-ground social-ecological studies examine relationships between forest conditions and types of institutions. Behavioral studies under controlled laboratory conditions enhance our understanding of explicit changes in structure that affect relevant human decisions. Evidence from all three research methods challenges the presumption that a single governance arrangement will control overharvesting in all settings. When users are genuinely engaged in decisions regarding rules affecting their use, the likelihood of them following the rules and monitoring others is much greater than when an authority simply imposes rules. Our results support a frontier of research on the most effective institutional and tenure arrangements for protecting forests. They move the debate beyond the boundaries of protected areas into larger landscapes where government, community, and comanaged protected areas are embedded and help us understand when and why deforestation and regrowth occur in specific regions within these larger landscapes.**

deforestation | reforestation | research methods | institutions | monitoring and sanctioning

In one of the most influential articles written in the last half century, Hardin (1) opened a major debate over the best property rights system for controlling overharvesting of shared natural resources.[e] Hardin recommended that governments impose public or private ownership on all natural resources, because resource users in what he called "the commons" are helpless to limit use patterns. Many social scientists have pointed out serious problems related to his assumptions and conclusions, including his confusion of open-access resources with closed-access shared or corporate resources (3, 4). Unfortunately, these strong critiques have not penetrated policy circles that still recommend simple solutions to the complex problems of resource governance. For example, many analysts and conservation biologists assume that unless forests are put under government ownership and protection, deterioration will result. For these scientists, public ownership of forests, preferably as a designated park, is the only way to achieve sustained conservation over time (5–7).

## Are Parks the Only Way?

Currently, >100,000 protected areas exist around the world and include ≅10% of Earth's forested areas (8). Many have received financial assistance from donors who have invested "heavily in extensive background studies and elaborate plans" (ref. 9, p. 39). Unfortunately, formal maps of these protected areas suggest a precision that cloaks the fact that many are "paper parks" with no effective control of their boundaries (10). Government-controlled protected areas also have generated substantial conflicts with local communities across the globe, in some cases threatening the long-term sustainability of these programs (11).

Some large-N studies of the effectiveness of protected areas rely on qualitative ratings by government officials and park managers rather than field studies (12–14). These assessments may introduce biases in the analysis and give rise to questions regarding subjective variations in perceptions of effectiveness among different observers (14–16). The much quoted study of protected area "effectiveness" by Bruner *et al.* (12) relies on a survey of park officials who were asked to evaluate the conditions inside their own parks and within a 10-km boundary outside the park. Asking people who have a vested interest in a particular outcome can bias surveys, no matter how large the sample, and it is not surprising the study found that public, strictly protected areas are effective. There are much sounder methods available for determining the relative success of public protected areas with various management and protection systems (16, 17). A recent metaanalysis of 20 studies of deforestation in and around protected areas, based on remote sensing, suggested that 32 of the 36 protected areas in the studies had faster deforestation outside the boundaries than within (ranging from 0.1% to 14% faster) (17). This finding suggests firmer evidence that public protected areas may have some degree of effectiveness but is also contradicted by studies like World Wide Fund for Nature International's examination (18) of >200 protected areas in 27 countries, which found that many protected areas lack financial and human resources and do not have effective control over their boundaries. Because of these conditions, some areas endure extensive and frequent conflicts (11, 19). However, in a stimulating new study, Nepstad *et al.* (16) broaden the debate by unpacking tenure arrangements in protected areas. In evaluating the impact of different tenure regimes, such as extractive reserves, indigenous territories, and national forests in Brazil, they found that under conditions of intense colonization pressures, strictly protected areas are much more vulnerable to deforestation and fire than indigenous reserves.

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Abbreviations: CIPEC, Center for the Study of Institutions, Population, and Environmental Change; CPR, common-pool resource; IFRI, International Forestry Resources and Institutions; MWS, Mahananda Wildlife Sanctuary; TATR, Tadoba-Andhari Tiger Reserve.

See accompanying Profile on page 19221.

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[e]Barrett and Mabry (2) noted that Hardin's article was the most frequently cited scientific article, having a major career impact by biologists included in their survey.

Thus, one should be skeptical of the claims that public protected areas are the only effective way to conserve forests. On the other hand, little evidence exists that turning forests over to local users is a guaranteed method to achieve effective conservation. Some communities manage their forests better than others (20–22). Although strong evidence exists that local communities are capable of creating robust institutional arrangements for governing local resources sustainably (4, 23, 24), some analysts have gone overboard and proposed community-based conservation as another cure-all. This thinking has led some donor-funded efforts to turn control over to local residents with a simple blueprint approach (25), generating little community involvement and enabling local "elite capture" of benefits (26).

It is becoming clearer that community management, under direct ownership, government concessions, or other long-term comanagement arrangements, has the capacity to be as effective or, under certain conditions, more effective than public, strictly protected areas (27, 28). The debate over the effectiveness of strictly protected areas therefore needs to be extended to a much larger landscape of tenure regimes that include various forms of comanagement, in which local communities have substantial management responsibilities and access to resources in and around a park, and a wide variety of community management types, from full ownership to community rights concessions on public lands to private management.

**The Challenge: Obtaining Reliable and Useful Data Regarding Forest–People Relationships.** Ecological systems rarely exist isolated from human use. To understand observations of existing resource systems, one must link the biophysical aspects of a resource with the ways that humans use and govern that resource and the incentives facing users and managers (29, 30). Governing natural resources sustainably is a continuing struggle (31). One must align the incentives of participants with the challenges they face, acquire adequate information concerning past and present conditions and uses of the resource, generate projections regarding future scenarios, and achieve consensus concerning what rules and institutional arrangements will govern the resource. The challenge of good scientific observation of linked social-ecological systems is made even more difficult because relevant variables operate at different scales and their impacts differ radically (32). Thus, it is important to develop better methods for studying these linked systems across multiple levels.

Because of these challenges, scholars seeking to understand the social-ecological factors related to forest management need to conduct long-term research programs that use research methods that focus at different temporal and spatial scales, such as time-series remote images, repeated on-the-ground social-ecological surveys of local stakeholders and their forests, and experimental laboratory studies. It is important to link empirical results obtained from multiple methods at diverse scales, in both natural and laboratory settings, to achieve holistic and multiscale comprehension of resource management problems. Incongruities in findings across scales should lead researchers to dig deeper into the reasons for scale-dependent outcomes. Mutual consistency in results across scales should reinforce the evidence. In this article, we provide an overview of findings from a long-term interdisciplinary, multiscale, international research program that studies factors affecting forest cover. This program analyzes remotely sensed images, conducts social-ecological measurements on the ground, and tests the impact of structural variables on human behavior in the experimental laboratory.

We focus on forests. Forests provide essential ecosystem services for the entire globe and basic commodities such as timber and nontimber forest products, help to regulate the world's water systems, and are the primary source of fuel for most of Africa and Asia. Global forest cover is dynamic and nonlinear, with important variations between and within temperate and tropical areas. For example, the Millennium Ecosystem Assessment found that "deforestation in the tropics occurred at an average rate exceeding 12 million hectares per year over the past two decades," whereas it also found that "the global area of temperate forest increased by almost 3 million hectares per year" between 1990 and 2000 (ref. 33, p. 29). But even within tropical forests, trends are not linear. Recent research has argued that forest transitions of net forest regrowth exceeding net forest loss are occurring in tropical forests in the Americas from the Amazon to southeastern Mexico (24, 34). Much of this forest regrowth in the tropics has been associated with the presence of robust community institutions and/or comanagement partnerships between communities and national governments (27, 28).

Thus, a basic question of key importance is "What types of policy interventions will help support or create local institutions, supported by higher-level institutions, to protect current forests and encourage positive local forest transitions?" Choices of property systems and land tenure will be central for new policies and institutional arrangements (27, 35). Finding answers to the question of what factors affect the likelihood of sustaining and enhancing existing forests and regeneration of past forested areas is important if contemporary deforestation patterns are to be reversed. Considerable data has been collected regarding the levels of deforestation and reforestation but at highly aggregated levels and for short time frames (36).[f] Whereas public actors tend to respond to larger-scale, regional-to-global socioeconomic and policy dynamics, the impact of their decisions is mediated by local-scale ecology and social structure (38). The relatively few long-term studies of forest growth, lack of reliable and comparable datasets across multiple countries, and relatively short time scales for which local-scale data are available exacerbate the difficulties involved in multilevel comparative studies (39).

In this article, we describe insights obtained from a series of explorations from the air (landscape scale), on the ground (forest-patch scale), and in the laboratory (individual decision-maker scale). Remotely sensed images generate important information regarding the landscape dimensions of forest processes and allow us to go back in time. They provide reliable measures of land-cover changes within different state and community management regimes. On-the-ground ecological and social studies provide evidence on variables associated with forest condition, which can be associated with institution type and rules. They enable us to understand how people living in or near a forest are organized (or not), what kinds of institutions they generate (or don't), what types of incentives officials and users face, and how these factors shape forest use and impact forest cover. Experimental laboratory studies enable assessment of explicit changes in structure that affect relevant human decisions and may suggest universal building blocks that are also used in crafting human decisions on resource use, thus enhancing efforts to understand issues such as overharvesting (23). Behavioral studies under controlled laboratory conditions enhance our understanding of complex, multivariable, and multiscalar human–forest interactions in the physical and social real world.

**From the Air: Over-Time Observations.** Satellite remote sensing is the most frequently used technique for mapping changes in forest cover (38). When combined with on-the-ground observations, studies of land-cover change enable us to analyze social incentives and actions and explore environmental and social change (39, 40). Based on a rigorous set of methods developed over the past decade at the Center for the Study of Institutions, Population, and Environmental Change (CIPEC), we have studied forests managed under a variety

[f]After an excellent review of econometric data on tropical deforestation, Kaimowitz and Angelsen (ref. 37, p. 104) concluded that they had "strong doubt about the value of producing more global regression models"; among the reasons for their warning was the "tendency to lose sight of strong micro-level relationships, which evaporate in the process of aggregating data."

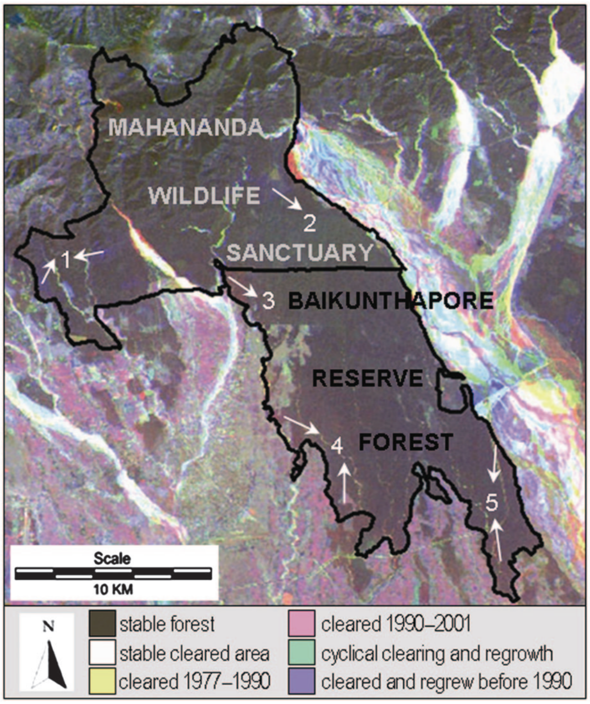


**Fig. 1.** Multitemporal satellite image color composite of landscape surrounding MWS, India. Blue, band 2 from 1977 Landsat MSS; green, band 3 from 1990 Landsat TM; red, band 3 from 2001 Landsat ETM.

**Fig. 2.** Electrified fence surrounding Mahananda Wildlife Sanctuary: keeping people out and wildlife in. (Photo by S. Pareeth, April 2004.)

of tenure arrangements across the world. Some public protected areas are protected only on paper, but effective management may occur under public, community, comanaged, or private ownerships (32, 41, 42). Formal ownership can be less important than the actual rules and mechanisms used to manage forests on the ground (online supporting material in ref. 31).

Our studies in South Asia are particularly illustrative. Forests in this priority region for conservation have some of the highest population pressures, with forest-dependent communities, emerging markets, and substantial conflicts over forest resources. A range of forest institutions coexist, from strictly protected national parks to comanagement of public protected areas to community concessions of public forest lands, providing an environment that facilitates careful comparative study of which policies, rule systems, and institutions assist effective forest conservation (43).

Time-series analyses of remotely sensed images enable us to identify trajectories of land-cover change at the landscape level. In Figs. 1, 4, and 7, we present multitemporal color composites from the Indian states of Maharashtra and West Bengal and the Chitwan District of Nepal. Each composite is generated from three Landsat satellite images of different dates by using the green band (band 2 of Landsat MSS and band 3 in TM and ETM images), which is sensitive to the presence of vegetation. This method provides a visual snapshot of patterns of land-cover change between three points in time from the mid-1970s to the recent past.

By overlaying boundaries of different management regimes on these images, we are able to interpret their impacts on forest change.[g] Through in-depth interviews conducted with local inhabitants, we can understand the major social factors associated with overharvesting in these forested landscapes. Detailed land-cover classifications, analyses of change trajectories, and landscape fragmentation studies corroborate these findings and are discussed in greater detail by Nagendra and colleagues (28, 42, 44).

Fig. 1 depicts the boundary of the Mahananda Wildlife Sanctuary (MWS) to the north, a national park with a substantial budget and protected by armed guards and electric fences (Fig. 2). To the south is the Baikunthapore Reserve Forest (BRF), another government protected area but assigned to a lower category of protection. The MWS contains relatively stable forests shown by a fairly uniform dark gray color, with some regrowth to the south (Fig. 1, blue, areas 1 and 2) that followed park establishment in 1976. The less protected BRF area has witnessed some degradation and thinning over time, shown by the lighter gray coloration and the reddish tint toward the northwest, southwest, and southeast boundaries (Fig. 1, areas 3–5). Despite monitoring by the Forest Department, substantial illegal timber harvesting continues, as Fig. 3 illustrates. Neither forest governance includes any comanagement practices. Residents in local communities frequently attempt to harvest timber, graze cattle, and engage in other illegal activities within the park, leading to conflicts with the Forest Department.

Fig. 4 portrays change in the Tadoba-Andhari Tiger Reserve (TATR) in central India. The central core has maintained forest cover since the mid-1970s, as can be seen by the predominantly dark gray color. Initial clearing toward the northwest and southeast (green patches in areas 1 and 2) was followed by regrowth when the park boundary expanded in 1986 to cover these areas. Yet, small,

**Fig. 3.** Bicycles and trucks confiscated from people caught illegally removing large logs from the MWS and BRF forests. Note the circular modification in the cycle frame (*Inset*) made to hold large logs of teak wood. (Photo by S. Pareeth, April 2004.)

[g]By keeping registration rms errors $<$0.5 pixels and doing careful visual comparisons by using overlay functions, we verified that the images overlapped exactly across the three image dates and that there were no sliver areas of misregistration. This precision was critical to ensure that any change we observed was due to real changes in land cover on the ground and not due to spatial mismatch at the boundaries.

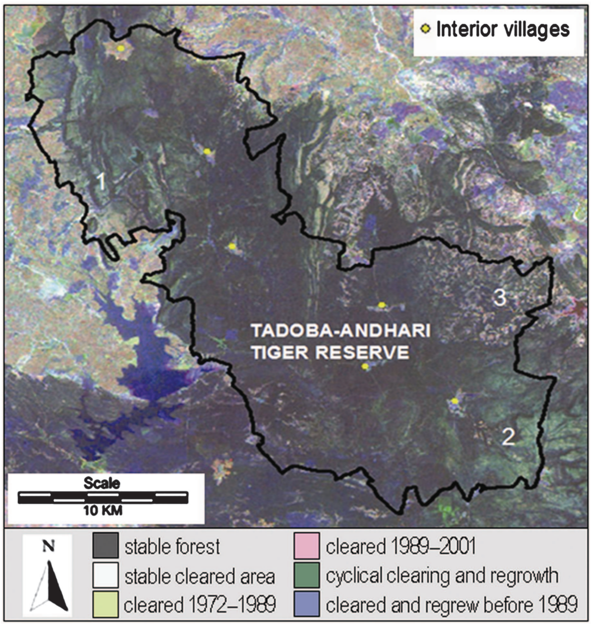


**Fig. 4.** Multitemporal satellite image color composite of area surrounding TATR, India. Blue, band 2 from 1972 Landsat MSS; green, band 3 from 1989 Landsat TM; red, band 3 from 2001 Landsat ETM.

stable patches of clearing (white, area 3) are clearly visible toward the east-central section. Here, the density of surrounding habitation is high and nearby urban markets generate incentives for illegal harvesting (42). As Figs. 5 and 6 illustrate, these activities continue to impact the park. The understaffed and ill-equipped guards working in this less prominent park are often unable to monitor the area adequately and enforce sanctioning measures on violators. When local people were briefly involved as allies in conservation activities during the late 1990s in a comanagement regime, forest monitoring and wildlife protection were seen to increase substantially. Yet, substantial conflicts between park guards and local people have expanded in recent years, partly because of plans to relocate interior villages outside the park (45). Thus, this underfunded public park with no consistent comanagement is maintaining forests in the interior, but showing some forest loss and fragmentation at the periphery.

Fig. 7 depicts land-cover change in comanaged buffer-zone forests adjoining the Royal Chitwan National Park (outlined in yellow) and community forests managed by local user groups on government lands (outlined in black). There is a visible contrast between the partial to complete forest recovery in these forests and

**Fig. 5.** Cattle enter the TATR boundary (marked by the yellow-topped pillar in the background) on their daily foraging beat. (Photo by H.N., December 2004.)

**Fig. 6.** Women harvest thatch grass from within the TATR while the forest ranger accompanying our research team looks on helplessly. (Photo by H.N., December 2004.)

the reddish-colored deforestation in the central area of the image, where mostly private landholdings are being increasingly converted to housing and agricultural use. The park itself is located to the south of the image; although not visible in this figure, our findings indicate that the park has been largely successful in maintaining forest cover in the central core, but some degradation has occurred at its periphery. Community forests (Fig. 7, C1–C8) and buffer-zone forests at a distance from the park gate (Fig. 7, B1–B3, B11, and B12) have been able to achieve some degree of forest regrowth, despite lacking the finances to invest substantially in forest plantation or development activities (28). Several buffer-zone forests located near the Royal Chitwan National Park main gate have achieved nearly complete regrowth after protection (Fig. 7, B4–B10). They receive more external technical and financial aid and much higher incomes from tourist visits that they can contribute to forest planting, maintenance, and monitoring (28).

Although rangers from the nearby Royal Chitwan National Park and the Forest Department make surprise visits to some of the buffer-zone and community forests, the substantial proportion of the monitoring is contributed by the communities, demonstrating their capacity to organize to successfully manage their forests under appropriate conditions. Results from field visits in May 2005 indicate that these communities have been able to protect their forests in the face of some very difficult and insecure situations after the intense conflicts within the country, signifying the resilience of their efforts. These comanagement initiatives have succeeded in reducing park-people conflicts, taking some pressure off the national park, and encouraging forest protection and regrowth in the larger landscape within which the park is embedded.

From these and other CIPEC studies (32), the official designation of a forest as government, community, or comanaged does not appear to impact forest conservation as much as the legitimacy of ownership and degree of monitoring that takes place on the ground. In the Nepal buffer-zone and community forests, where user groups are provided with secure tenure rights to their forest resources and ownership is perceived as legitimate and fair, communities themselves engage in monitoring efforts to successfully manage their forests. Although traditional, strict public protection of parks can work to protect forests, it has a high fiscal cost and a high cost in terms of increased conflicts with local communities. This situation is clear in the MWS, where the government has the main responsibility to safeguard forests from overharvesting by using approaches that involve guards with guns and protection by electric fences. Such approaches are not feasible in all government protected areas, as seen in the BWR and the TATR, and come at the expense of increased conflicts with local communities, indicating the difficulties in sustaining such efforts over the long term.

**From the Ground: Cross-Sectional Data.** Let us turn to an overview of studies examining the performance of diverse institutional arrange-

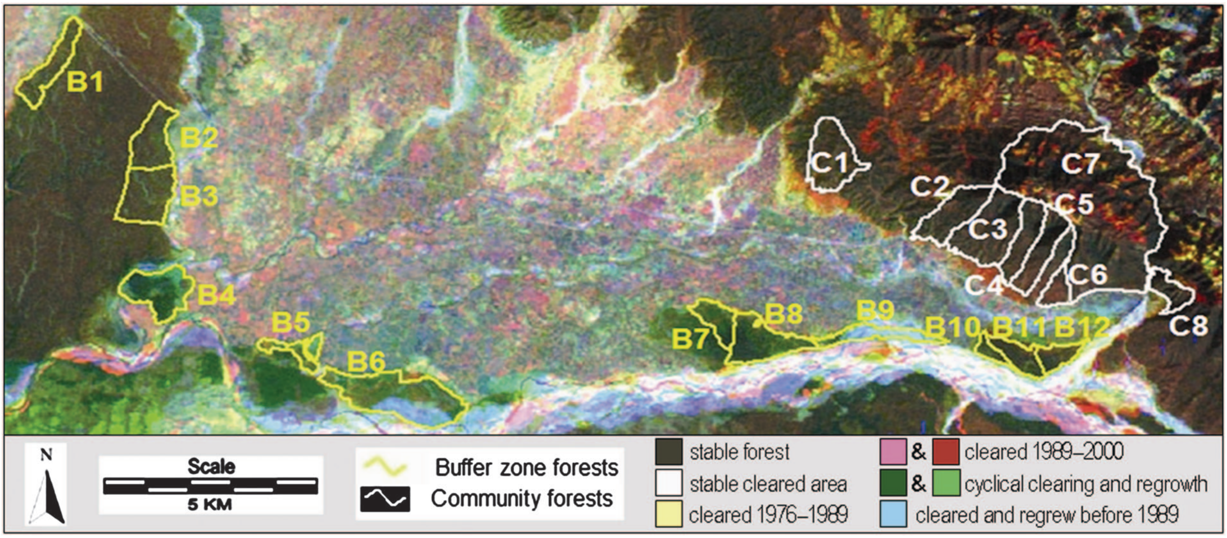


**Fig. 7.** Multitemporal color composite of east Chitwan district, Nepal. Blue, band 2 from 1976 Landsat MSS image; green, band 3 from 1989 Landsat TM image; red, band 3 from 2000 Landsat ETM image.

ments by using on-the-ground measures. For this section, we rely on data gathered by the International Forestry Resources and Institutions (IFRI) research program initiated in 1992. Two years of intense development and review by ecologists and social scientists around the world led to the creation of 10 research protocols for obtaining reliable information regarding users and forest governance and the ecological conditions of sampled forests. A long-term collaborative research network was established with centers located in Bolivia, Colombia, Guatemala, India, Kenya, Mexico, Nepal, Tanzania, Thailand, Uganda, and the United States, with supporting research in Madagascar and Brazil (see refs. 20 and 46).

In an effort to examine whether government ownership of protected areas is necessary for improving forest density, Hayes and Ostrom (47) compared the rating of forest density (on a five-point scale shown in Table 1) assigned to a forest of a protected park or other property regime by the forester or ecologist who had completed supervising the forest mensuration of trees, shrubs, and groundcover conducted in a random sample of forest plots.[h] This ranking rates the vegetation density of the forest in comparison to the normally observed density for the ecological zone within which the forest is located, thus generating a measure of forest condition that is comparable across different ecological regions. We analyzed 163 forests located in the countries listed above, of which 76 were government-owned forests that were legally designated as protected forests and 87 were public, private, and community-owned forested lands used for diverse purposes. As shown in Table 1, no statistical difference exists between the forest densities related to officially designated protected areas contrasted with other property regimes. Thus, other institutional and tenure arrangements can work as well as government-owned protected areas in the maintenance of vegetation density.

We also have shown that the monitoring activity undertaken by the users themselves is related to forest density. Gibson *et al.* (49) examined the rule-monitoring behavior of 178 forest user groups studied as part of the IFRI research program. In group interviews with members of user groups, researchers ask about the regularity with which users monitor the rule conformance of other users.[i] We found a strong correlation between the level of monitoring and forest density, controlling for whether users were formally organized, whether the users heavily depended on a forest, and the level of social capital within a group. Detailed field studies (50–52) and metaanalyses (53) illustrate the feasibility of achieving high levels of forest protection under diverse property regimes when local people participate in monitoring.

**From the Ground: Over-Time Data.** A long-term goal of the IFRI research program is to use the forest mensuration data collected at each site to compare measures over time for the same forest (thus, holding the ecological zone constant over time). Number of stems, diameter at breast height (DBH), and basal area were obtained for all trees within a 10-m circumference of a set of randomly sampled plots.[j] We now have longitudinal data from 42 forests: 5 in India, 3 in Kenya, 10 in Nepal, 18 in Uganda, and 6 in the United States. These forests do not constitute a random sample of all of the IFRI forests we have studied, but rather those where research colleagues have been able to return for a second field visit.[k]

For each forest, we determined whether our measures for basal area, DBH, and number of stems had increased (+), decreased (−), or remained unchanged (0) at a second visit to the forest by using a two-tailed $t$ test ($P < 0.1$). In Table 2, we array these dependent variables by forest ownership types. Few of the forests have shown substantial improvement over time, which may be due to the relatively short time between visits (average of five years). However, a higher percentage of community forests than government forests were characterized by measures that had increased or were the same. Individually owned private forests are primarily characterized by similar or increased measures over time, but the sample (five) is too small to draw definite conclusions.

In Table 3, we present the results from a one-way ANOVA to

[h]Extensive forest mensuration is conducted at every IFRI site at the same time information is obtained regarding forest users, their activities and organization, and governance arrangements. Comparing forest measures across ecological zones is misleading because measurements such as the average diameter at breast height in a forest are strongly affected by precipitation, soils, elevation, and other factors that vary dramatically. Thus, we ask the forester or ecologist who has just supervised the collection of forest data to rate the forest on a five-point scale from very sparse to very abundant.

[i]User group monitoring and sanctioning was coded as never, occasionally, seasonally, or year round. For purposes of the analyses reported here, never or occasionally were recoded as sporadic, whereas seasonally and year round were coded as regular. The variable focuses on the level of effort that a user group devotes to monitoring established rules.

[j]We focus on changes in basal area, stem count, and DBH, because they provide estimates of forest density and maturity that enable us to assess trends in forest condition over time.

[k]Data exist for a third site visit for some forests, but we concentrate here on those with two.

**Table 1. Comparison of vegetation densities in parks and nonparks**

| | Vegetation density | | | | |
|---|---|---|---|---|---|
| | Very sparse | Somewhat sparse | About average | Somewhat abundant | Very abundant |
| Officially designated parks, % ($n$ = 76) | 13 | 21 | 36 | 26 | 4 |
| Nonparks, % ($n$ = 87) | 6 | 22 | 43 | 26 | 3 |

Kolmogorov–Smirnov $Z$ score = 0.472, $P$ = 0.979; no significant difference. Adapted from ref. 47, p. 607; ref. 48, p. 23.

assess whether significant associations could be observed between management regimes and changes in forest condition or between regular monitoring of forests and changes in forest condition. Consistent with the earlier cross-sectional analysis of Gibson *et al.* (49), we find that the type of ownership of these 42 forests does not have a statistically significant relationship with any of these three dependent variables. On the other hand, and consistent with our other analyses, we find that the involvement of at least one user group in regular monitoring of conformance to the rules related to entry and use patterns is significant.

**From the Laboratory.** Findings that users of forest resources are willing, in some settings, to undertake costly cooperative activities including monitoring are consistent with other field studies of resource use (27, 43, 54–56). Repeated field observations of users taking costly actions to create, monitor, and enforce rule systems are, however, contrary to predictions derived from the standard economic model of individual choice that assumes individuals maximize short-term, material payoffs (ref. 57, see also ref. 1). The benefits of well enforced rules regarding entry and harvesting from a resource are shared by all members of a group, whereas the costs are borne by the individual. Thus, the repeated findings from the field of high levels of cooperation challenge core economic theories of human behavior.

Field settings are complex. It is difficult to sort out which of many variables affect the willingness of individuals to engage in costly actions that produce group benefits. To help address this theoretical puzzle, we have conducted a series of laboratory experiments of behavior in common-pool resource (CPR) situations (58, 59). In the laboratory, we change one structural feature of a CPR situation at a time to assess the specific differences in outcomes obtained across experimental designs. In the experiments reported below, we used the mathematical model of maximum sustainable yields that is used in most environmental science textbooks to predict overharvesting when multiple users can freely harvest from a CPR.[l]

Using this model, initial harvesting yields increasing returns. Net returns begin to fall, however, once harvesting exceeds the optimal level. When each harvester pays full attention to his/her own returns rather than to group returns, the game-theoretic prediction based on income maximization is of substantial overinvestment. In the laboratory, the "harvesters" are undergraduate students at Indiana University who voluntarily agree to participate. For all experiments reported below, we recruited eight subjects who received an endowment of 25 tokens in each decision round. They were given a choice between investing these tokens in Market 1, an outside opportunity that returned \$0.05 for every token invested, or in Market 2, the CPR, with the concave production function of $23(\Sigma x_i) - 0.25 (\Sigma x_i)^2$. Subjects could earn \$1.25 per round if they invested all of their tokens in Market 1.[m] The return from investing any token in Market 2 depended on how many tokens all members of the group invested. A group investment of 36 tokens in Market 2 yields the optimal individual return of \$1.89 per round.[n]

In our baseline experiment, eight subjects anonymously made decisions each round at a computerized work station. No communication was allowed. After each round, they were informed of the total tokens invested by all subjects (Table 4, row A). As predicted, subjects substantially overharvested in the baseline experiments. Subjects averaged 21% of the maximum attainable returns from their investments (see Table 4).

Next, we changed the baseline experiment to allow subjects to engage in face-to-face communication for one period after they had experienced 10 rounds of the baseline experiment (Table 4, row B) (58). After a 10-min period in which subjects were brought to a common area for open discussion, they returned to their computer terminals, where they anonymously made independent decisions in all remaining rounds. The game-theoretic prediction for this design (Table 4, row B) is the same as for the baseline experiment. Mere "cheap talk" is not considered sufficient to change behavior. Contrary to theoretical predictions, however, given a single opportunity to discuss potential joint strategies and to encourage each other to keep promises, subjects increased their joint returns to 55% of the maximum.

After the 10th round of the repeated communication design (Table 4, row C), we enabled subjects to talk face-to-face between all further rounds. Subjects increased their average net yield to 73% of the maximum. The subjects effectively used the opportunity for repeated cheap talk. Our findings are consistent with many experimental studies of social dilemmas that have found that face-to-face communication greatly increased cooperation (60, 61).

Next, we examined the impact of a diverse set of sanctioning experiments (Table 4, rows D–F2). In all sanctioning experiments, the subjects themselves decided whether to pay a fee to fine another player, knowing that the fine would be subtracted from the other player's payoff. In all of these experiments, the subjects were shown a table after each round that listed the specific CPR allocations of all of the subjects arrayed by an assigned number that maintained anonymity.

In the first set of eight sanctioning experiments (Table 4, row D), the sanctioning rules were imposed by the experimenters after 10 rounds of the baseline design. The subjects were told that after all future rounds they would complete a form instructing the experimenter to subtract any fees they volunteered to pay and to subtract the related fine from the payoffs of a subject known only by an assigned computer number. Subjects were very willing to pay a cost to impose a fine on other players. This willingness increased with lower fees and as the fine-to-fee ratio grew larger. Subjects increased the average net yield achieved in these experiments above baseline experiments (37% compared with 21%). When the fees and fines were subtracted from payoffs, however, the average net

[l]The mathematical structure of our baseline experiment assumes a fixed number of harvesters $n$ with access to a CPR. Each harvester $i$ receives an endowment $e$ of resources that can be invested in a CPR or in a safe outside activity $w$. One can think of a resource user having a fixed endowment of time each decision period that can be invested in appropriating from the resource or in working for someone else at a fixed wage. The payoff to the harvester from the CPR depends on aggregate group investment and on the individual's investment as a percentage of the total. Let $x_i$ stand for a harvester's investment in the CPR, where $0 \leq x_i \leq e$. The group return is given by a production function $F(\Sigma x_i)$, where $F$ is a concave function: $F(0) = 0$, $F'(0) > w$, and $F'(ne) < 0$.

[m]The concept of investing in alternative markets is more intuitive for undergraduate students than asking them to play-act as if they were forest users, fishers, or irrigators. We wanted subjects to take these experiments seriously. Payoffs were presented to students and are reported here in "lab dollars." Students were paid one-half of their total computerized earnings and usually earned more than \$25 per experiment session, which lasted ≈1.5 h, with time devoted to instructions and initial trial decisions to ensure the subjects thoroughly understood the experiment.

[n]The predicted Nash Equilibrium for this game was for all participants to invest eight tokens each, or 64 tokens, in Market 2. If all invested at the predicted Nash Equilibrium, they would each earn \$1.55 (lab dollars) per round.

**Table 2. Percent forests with significant change in forest measures between first and second site visits**

| Dependent variables | Government forests ($n$ = 22) | | | Community forests ($n$ = 15) | | | Private forests ($n$ = 5) | | |
|---|---|---|---|---|---|---|---|---|---|
| | Lower | Same | Better | Lower | Same | Better | Lower | Same | Better |
| Basal area, % | 40 | 55 | 5 | 20 | 53 | 27 | — | 100 | — |
| DBH, % | 23 | 68 | 9 | 20 | 53 | 27 | — | 80 | 20 |
| Stems, % | 50 | 45 | 5 | 40 | 33 | 27 | 40 | 60 | — |

yield was only 9%, much lower than achieved in the baseline (58). Bochet *et al.* (61) also found that punishment systems designed by experimenters had little net effect on efficiency.

The next sanctioning experiment (Table 4, row E) gave subjects an opportunity for a 10-min communication round after they had learned the details of the fee and fine structure. In two of the three experiments in this design, subjects used communication to develop joint decision strategies relatively close to optimal and, thus, paid few fees to fine defectors. In the third experiment, subjects did not agree on a joint strategy, and the returns were lower and more fines were paid than in the first two experiments of this design. Across all three experiments of this design, subjects increased their average net yield as a percent of maximum (to 85%), but after fees and fines were subtracted, their average net yield fell to 67%.

The last set of experiments (Table 4, rows F1 and F2) brought back subjects who had been in a previous sanctioning experiment and gave them a one-shot communication opportunity to choose whether they would implement their own sanctioning institution. Two of the groups (Table 4, row F1) decided that they did not need a sanctioning system but needed only to agree on a joint strategy. Without continued communication, the joint strategy fell apart and defection rates escalated. In the other four experiments (Table 4, row F2), the subjects decided on a joint strategy and a fee-to-fine ratio of their own choice. In these experiments, the subjects achieved an average net yield of 93% of the maximum, faced few defections, and, thus, achieved 90% of maximum yield even after fees and fines were subtracted. In summary, across all experiments, subjects achieved the highest payoffs when they decided on their own sanctioning system and joint decision strategy.

These baseline and communication experiments have been replicated by Cardenas and colleagues (62, 63) and Casari and Plott (64). The finding that participants in social dilemma situations are willing to sanction each other has been extensively replicated in varied designs (65–67). A recent study demonstrates that when diverse groups of subjects facing experimental social dilemma situations compete for members, groups who do not adopt a sanctioning system find their joint earnings dissipating, whereas groups who adopt a sanctioning system obtain higher outcomes and draw members from the other groups (68). A theoretical explanation for the above findings from the field and the laboratory is presented by Ostrom (23, 69).

**Table 3. Impact of formally designated tenure and forest monitoring on changes in forest condition, an assessment by using ANOVA**

| Independent variables | Change in DBH | Change in basal area | Change in stem count |
|---|---|---|---|
| Ownership,* $F$ | 0.89 | 2.52 | 1.00 |
| Regular involvement of user groups in monitoring rules,† $F$ | 0.28 | 10.55‡ | 4.66§ |

*Government, community, private: all $F$ statistics for ownership have 2.39 degrees of freedom.

†At least one user group is regularly involved in monitoring of rules of forest use; all $F$ statistics for monitoring have 1.38 degrees of freedom.

‡Significant at 0.05.

§Significant at 0.01.

## Discussion

Evidence from all three research methods challenges the presumption that a single governance arrangement will control overharvesting in all settings. The temptations to overharvest from natural resources are always large. If the formal rules limiting access and harvest levels are not known or considered legitimate by local resource users, substantial investment in fences and official guards to patrol boundaries are needed to prevent "illegal" harvesting. Without these expensive inputs, government-owned, "protected" forests may not be protected in practice. On the other hand, when the users themselves have a role in making local rules, or at least consider the rules to be legitimate, they are frequently willing to engage themselves in monitoring and sanctioning of uses considered illegal, even of public property. When users are genuinely engaged in decisions regarding rules that affect their use, the likelihood of users following the rules and monitoring others is much greater than when an authority simply imposes rules on users. These results help to open up a previously undescribed frontier of research on the most effective institutional and tenure arrangements for protecting forests, from public protected areas to private forests to community forests, under various conditions. Entering this frontier moves the debate beyond the internal and external boundaries of protected areas into much larger landscapes where protection also occurs and helps us understand when and why protection, recovery, and clearing occur in specific regions within these larger landscapes.

We conclude that simple formulas focusing on formal ownership, particularly one based solely on public ownership of forest lands, will not solve the problems of resource overuse. This finding is consistent with Dietz *et al.* (31), who show that more important than the particular form of ownership is whether boundaries of linked social-ecological systems have been well established in the field as legitimate and whether regular monitoring and enforcement of rules related to entry and use exist. Solutions to overharvesting of natural resources take time and effort to design so as to fit a local ecology and the social structure of the users and officials involved and to avoid crowding out intrinsic motivation (22, 29, 70).

We do not advocate using fences and guns to protect government forests or turning forests over to communities as the only answers to the problem of deforestation. Nor do we think that strict preservation of forests is the only important outcome to be achieved in all forests. Although forest conservation is a crucial goal in the 21st century, we are also concerned regarding the importance of forests for the livelihoods of people and equity in the distribution of benefits from forests, biodiversity, and many other outcomes. Our evidence from the field and the laboratory shows that the earlier assumption that no users would voluntarily contribute to making rules or enforcing them is false. On the other hand, assuming that all individuals will cooperate to solve resource dilemmas under all conditions is also false.

Focusing on monitoring alone is not sufficient when policy makers do not involve those living in and near forests in decisions, do not clearly define boundaries, rely on only one institutional type,

**Table 4. Aggregate results of CPR experiments**

| Experimental designs by using 25 token endowments | Average net yield as % of maximum | Average net yield minus fees and fines | Defection rate | No. of experiments |
|---|---|---|---|---|
| (A) Baseline experiment: No communication | 21 | — | — | 3 |
| (B) One-shot communication | 55 | — | 0.25 | 3 |
| (C) Repeated communication | 73 | — | 0.13 | 6 |
| (D) Imposed sanctioning institution | 37 | 9 | — | 8 |
| (E) One-shot communication and imposed sanctioning institution | 85 | 67 | 0.01 | 3 |
| (F1) One-shot communication with endogenous choice of sanctioning institution, none chosen | 56 | — | 0.42 | 2 |
| (F2) One-shot communication with endogenous choice of sanctioning institution, sanction chosen | 93 | 90 | 0.04 | 4 |

Adapted from ref. 57, p. 414. Nash Equilibrium for all designs is a net yield of 39% of maximum.

use the same rules in all ecological settings within their jurisdiction, and impose uniform sanctions. Solving problems of resource monitoring is a necessary but not a sufficient condition for sustainability. Unless one ensures the livelihoods of those living around or within a forest, a major investment in monitoring alone is not a sufficient, long-run management strategy and may even be counterproductive. Further, focusing on a single research method used by one academic discipline for understanding complex, multiscale processes does not provide a cumulative understanding of how individuals in dynamic, complex, social-ecological settings react to institutional rules and affect ecological systems. Multidisciplinary research in diverse international settings is essential for developing an integrated perspective to achieving sustainability.

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