Integrating fisheries approaches and household utility models for improved resource management

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Natural resource management is littered with cases of overexploitation and ineffectual management, leading to loss of both biodiversity and human welfare. Disciplinary boundaries stifle the search for solutions to these issues. Here, I combine the approach of management strategy evaluation, widely applied in fisheries, with household utility models from the conservation and development literature, to produce an integrated framework for evaluating the effectiveness of competing management strategies for harvested resources against a range of performance metrics. I demonstrate the strengths of this approach with a simple model, and use it to examine the effect of manager ignorance of household decisions on resource management effectiveness, and an allocation tradeoff between monitoring resource stocks to reduce observation uncertainty and monitoring users to improve compliance. I show that this integrated framework enables management assessments to consider household utility as a direct metric for system performance, and that although utility and resource stock conservation metrics are well aligned, harvest yield is a poor proxy for both, because it is a product of household allocation decisions between alternate livelihood options, rather than an end in itself. This approach has potential far beyond single-species harvesting in situations where managers are in full control; I show that the integrated approach enables a range of management intervention options to be evaluated within the same framework.

hunting | bushmeat

Management Strategy Evaluation (MSE) is fast becoming the dominant framework for the development and assessment of management procedures for commercial fisheries (1, 2). This powerful approach uses simulation in a virtual environment to test the robustness of potential management strategies to a range of uncertainties. Unlike traditional approaches, MSE explicitly models the whole management system; not just the resource stock and its reaction to different harvest rules, but the gathering of data, the conversion of those data into a harvest rule, and the implementation of that rule (3). This approach then allows fisheries scientists to evaluate the effects of a lack of knowledge or understanding on the performance of a range of harvest rules. The management advice that comes from MSEs is nonprescriptive and probabilistic, enabling stakeholders to evaluate the tradeoffs inherent in choosing one or other management procedure. Indeed, one of the strengths of MSE is that it can encourage the participation of stakeholders, both in defining the metrics against which the performance of harvest rules can be evaluated, and in the generation of scenarios for testing the robustness of these rules, leading to greater buy-in to the eventual agreed procedure (4).

Although MSEs have been extensively and almost exclusively applied to commercial fisheries to date, the approach has substantial potential in other areas of resource management—wherever large-scale experimentation to resolve uncertainty is impracticable. However, the applicability of current MSE models is limited by their general lack of realism in the modeling of harvester behavior. Illegal exploitation is a recognized problem for commercial fisheries and is a key reason why the outcome of fisheries management may differ from managers' expectations (5). Despite this issue, the majority of past and current research into MSEs is still focused on the uncertainties surrounding the resource population and its observation, rather than on the implementation of harvesting rules (1, 3; but see refs. 6 and 7).

Generally, MSEs assume that rules are implemented either as they stand or with error, making them unrealistic for use in situations in which resource user decisions deviate systematically from management prescriptions. This situation encompasses many exploitation systems in the developing world in which small-scale users are harvesting for subsistence use or local sale and making decisions at the household level. Households act very differently to firms, because they often exploit the resource as one of a suite of productive activities, and their aim is not to maximize profits but to maximize household welfare, or utility. There is a long-standing and thriving modeling literature that addresses household decision making in conservation, in situations where households have multiple livelihood activities. The literature mostly addresses the effectiveness of Integrated Conservation and Development Projects in the context of protected area management and draws on economic models of agricultural household behavior (e.g., refs. 8–11).

Standard harvesting theory, which generally underlies MSEs, is poorly equipped to represent human welfare. Generally fisheries MSE performance metrics still focus on profit maximization and stability of yield subject to a conservation constraint, on the assumption that these outputs are good proxies for human well-being. In the case of commercial fisheries they may well be so, although the bioeconomic models that underlie economic performance metrics in MSEs are still poorly developed and underevaluated (12). However, in artisanal and subsistence harvesting systems, when households are trading off livelihood options to maximize household utility, standard fisheries performance metrics are inadequate for determining whether an intervention is improving well-being. Utility is a function of consumption rather than of profit. Harvested goods can be consumed directly or sold to allow purchase of other goods. All productive household activities contribute to utility. For example, increasing the price obtained for agricultural crops may shift labor allocation to agriculture and, consequently, increase utility directly via improved purchasing power for other goods. It may also cause investment in new harvesting gear (such as a gun), a consequent shift in harvesting target toward more saleable species, which may shift household production from consumption to sale of wildlife; the overall effect on sustainability is ambiguous (13). If we are to use MSEs to evaluate the robustness and performance of conservation interventions in developing countries, we need a metric for human well-being. The addition of a household component to the framework leads to

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change in utility being a directly measurable output from the model, which can be used to evaluate management performance.

In this paper, I illustrate how a household utility model can be integrated within a MSE framework, and demonstrate the power and flexibility of this new approach, as well as some of the difficulties and considerations involved in model development. I use a very simple model to do this, structured and parameterized to represent a single species being exploited by households who also farm—an abstraction similar to that used by other authors (e.g., refs. 8 and 9). I use this model to address a few key questions that demonstrate the potential power of this integrated MSE approach. Because the model is not parameterized to any particular case study, it has limited real world applicability but heuristic power. The questions addressed are as follows:

How does including a household utility component to the MSE framework affect the performance of simple harvest rules, and how does this differ depending on whether the manager accounts for household decision making in their formulation of the harvest rule?

How do utility, harvest, and resource stock-based performance metrics compare?

What are the effects of different specifications of market structure and returns to labor from harvested and farmed products on the behavior of the model?

How should managers trade off investing in monitoring the resource stocks to reduce uncertainty against investing in law enforcement to reduce illegal harvesting by the resource users at different levels of the penalty for illegal harvesting?

What is the difference between a utility-based management objective and a yield-based objective, in terms of the predicted performance of the harvest rule and manager decision making?

Modeling Framework

Standard MSEs. MSEs generally consist of four submodels: the "operating model" (OM), which is the representation of the dynamics of the resource stock; the "observation model," which represents the process of the manager collecting data about that population; the "assessment model" in which the manager uses the data collected to generate a harvest control rule (HCR); and the "implementation model" in which the rule is implemented, generating a harvest that feeds into the operating model to produce the next time-step's resource population (Fig. 1 *Upper*).

Various kinds of uncertainty can be represented and tested in these models. For example, the observation model captures observation uncertainty, the implementation model captures the uncertainty related to the failure of actual harvests to match the HCR (which may result from simple stochasticity or intentional harvester behavior), and the OM includes both parameter uncertainty (lack of knowledge about the parameter values), process uncertainty (e.g., environmental variation affecting the population), and structural uncertainty (lack of knowledge about the system, e.g., the form of the density dependence). Some types of uncertainty (e.g., parameter uncertainty) are built into the models, whereas others (e.g., structural uncertainty) are tested for by running alternate versions of the OM.

The assessment model mimics the procedure by which the manager uses available data to generate an HCR. In some cases, they will use a model-based approach, including using a version of the OM to generate the rule. In other cases, they may use an empirical approach in which a statistical model is fitted to the observed data but no underlying mechanism is assumed (14). A typical HCR might specify a fishing mortality rate or total allowable catch that is a function of the estimated stock size, with a limit stock size below which harvest rate declines, and another

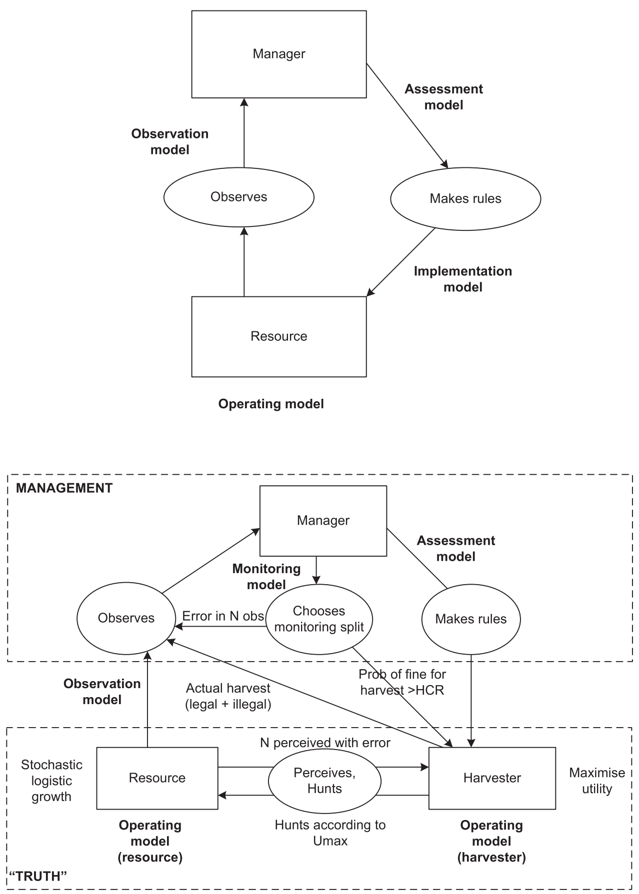

Fig. 1. Schematic representations of management strategy evaluation models. (*Upper*) A standard fisheries MSE, with four submodels: the resource operating model (OM) representing the "truth"; the observation model; the assessment model for calculating the harvest control rule; and the implementation model by which the HCR is implemented. (*Lower*) The integrated model. The harvester OM replaces the implementation model, and a monitoring model is added that splits the manager's budget between reducing uncertainty in the observation model and increasing the probability of detection of illegal harvest.

limit below which harvesting is suspended. The assessment model determines the rate and limits for the HCR depending on the manager's objectives. A number of different HCRs (both in terms of their structure and the harvest levels) may be generated and tested.

To carry out an MSE, the researcher specifies performance metrics, which are output variables that give information about the performance of the system in relation to management objectives. Objectives can be quantitatively stated; for example, a common one may be to maximize yield subject to the constraint that the population size does not fall below a threshold. Next, a set of operating models and conditions are developed for testing the competing HCRs. These models include the "best guess" at the true dynamics of the population, but also realistic alternative OMs, as well as a range of options for the values of particularly important and uncertain parameters (such as the slope of the density dependence function or the degree of bias in observations). The aim is to test the HCRs not just under realistic conditions, but in situations in which the manager's perceptions are potentially very wrong, to see how robust the HCRs are to uncertainty (15). The HCRs are tested for each model set by running the simulation many times, generating summary statistics for each of the performance metrics, in order for decision makers to be able to make informed decisions about the tradeoffs they face in deciding on their HCR. An MSE does not come up with a "best" answer but leaves these decisions to the manager (14).

Integrated Model. The proposed integrated model retains all of the MSE elements but adds a second harvester operating model, replacing the implementation model (Fig. 1 *Lower*). This model represents household decision making, and links the assessment model to the resource OM indirectly, via the HCR's effect on the harvesting behavior of resource users. I also introduce a monitoring model to investigate the manager's tradeoff between monitoring the resource stock (to reduce the uncertainty in the observation model) and enforcing the HCR (to increase the cost of illegal harvesting with the aim of reducing the discrepancy between actual and desired harvest levels). This monitoring tradeoff demonstrates the additional power of the integrated model approach to address wider resource management dilemmas than just the form of the HCR.

Results

Including Harvester Decisions. Under the default parameter values, and using a model in which there is no harvester decision making, such that the HCR is implemented as stated, the harvested population equilibrates at an average of 64% of carrying capacity (K) when the HCR is set such that the population has a <5% chance of falling below the conservation threshold of 30% of K. Without harvester decision making but with the manager aiming to maximize yield over the reference period (years 30–50 of the simulations), the population equilibrates at ≈44% of K. This equilibrium level is <50% because the harvester is maximizing yield in the medium rather than long term, and because of observation and parameter uncertainty. Finally, if the manager has no control over the harvester, who then harvests at the open access rate, the average equilibrium population is 39% of K and the conservation threshold is breached in 35% of years.

When harvester decision making is included in the model, management effectiveness is strongly determined by the penalty for overharvesting. If the penalty is low, then the informed manager allocates all their resources to law enforcement in an attempt to reduce the illegal harvest below the acceptable threshold. This allocation maintains the performance metrics at reasonable levels. If the manager does not take harvester behavior into account, they instead allocate their resources to population monitoring, and performance is poor. If the penalty is high, then the default resource allocation to law enforcement (assumed to be 0.5) is enough to deter users from overharvesting and an informed manager is able to allocate more resources to population monitoring, in the knowledge that there is no need to allocate >10% of the budget to law enforcement to meet the monitoring performance criterion. Detailed results are given in the *SI Appendix*, Table S2 and Fig. S1.

The performance metrics based on resource stock size and utility are strongly correlated (*SI Appendix*, Table S3). The relationship between the harvest and the other metrics is less straightforward, however. The actual harvest by the resource users is not strongly related either to utility or to the stock conservation metric. The legal harvest specified in the HCR is, however, strongly related to both. The legal harvest rate is a product of manager decision making, based on resource stock sustainability; hence, these two metrics are strongly correlated, whereas the actual harvest rate is a consequence both of the manager's decisions and the household's harvesting decisions, which are not based on stock conservation criteria. When the legal harvest increases, so does utility in a straightforward manner. However, the actual harvest includes an illegal component, the profitability of which depends on both the harvest and the expected penalty. The result is a nonlinear relationship between the amount of illegal harvesting the household decides to undertake and the resultant household utility (*SI Appendix*, Fig. S2). These results suggest that, when household decision making is involved, metrics based on the amount harvested are less robust than utility- and resource stock-based metrics, because the harvest is an intermediate rather than an ultimate measure of both management performance and human welfare.

Sensitivity to Changes in the Harvester Model. The predictions of the harvester OM are highly sensitive both to the elasticities of the returns to labor (i.e., the change in output with a one unit change in the labor allocated to a particular activity) and to assumptions concerning market access. The allocation of labor between the two productive activities, and the resultant resource stock size, depend on both the absolute and relative values of the returns to labor elasticities, β_H and β_F. When harvested produce is sold but agricultural produce is consumed at home, there is a continuous relationship between β_H and labor allocation to harvesting. However, when both forms of produce are sold, the model becomes very sensitive to small changes in the elasticities, shifting suddenly to a low labor allocation/high population size state as β_H increases; the point at which this shift happens depends on the value of β_F. This result is because the tradeoff between productive activities occurs within the budget constraint rather than in the utility optimization (*SI Appendix*, Fig. S3 and Table S4). These sensitivities combine to make the results of the baseline model vary substantially as assumptions about the structure and parameter values of the household OM change (*SI Appendix*, Table S5), underlining the importance of ensuring that the structure chosen for the household OM is representative of the system being modeled, as well as the need for MSEs to include full testing of the robustness of HCRs to the effects of both model and parameter uncertainty in the household OM.

Budget Allocation Tradeoffs. The manager makes two decisions—the HCR and the allocation of resources between population monitoring and law enforcement. The main exogenous influence on the outcome of the allocation decision is the penalty that can be imposed on noncompliers. If the HCR is a simple proportional harvesting mortality, then the allocation of resources to law enforcement is negatively related to the size of the penalty; when the penalty is large, less law enforcement is required to keep illegal harvesting within the prescribed limit (Fig. 2*A*). When the penalty is small, the manager must invest all their resources in law enforcement, and this amount is still not enough to prevent overexploitation. As the penalty increases, the household's labor allocation to harvesting decreases and stabilizes, and the divergence between the HCR and the actual harvesting level declines, as one rises and the other falls (Fig. 2*B*).

The effect of including a household OM in the MSE can be seen in the manager's allocation and HCR decisions. If harvesters do not make independent decisions, the manager has no need to monitor harvesters and allocates all resources to population monitoring, producing a high population size and harvest level. If there is household decision making, but the manager ignores it, no resources are put to law enforcement, and so the harvesters harvest at a higher, open access, rate and the population is low; the consequent low HCR is ineffectual (Fig. 2*B*).

When the manager varies the HCR to meet particular objectives, such as maximizing yield or long-run household utility, the overall picture is similar, although more variable (*SI Appendix*, Fig. S4). The manager who aims to maximize yield has a different approach to law enforcement than the utility maximizer. The yield maximizer keeps a low allocation to law enforcement throughout, such that the household can effectively harvest as they wish; labor allocation to harvesting remains high as the penalty increases, and the stock is heavily harvested. The manager who aims to maximize utility keeps the resource stock high by allocating resources to law enforcement, particularly at low penalties, and this strategy means that labor allocated to har-

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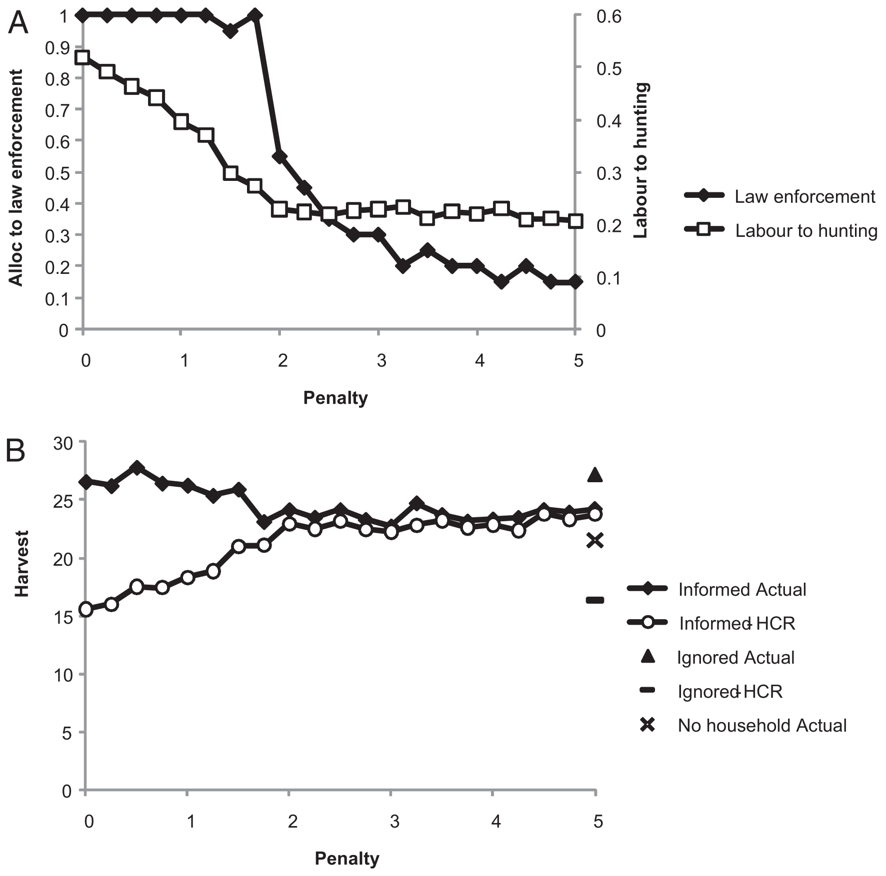

Fig. 2. Tradeoffs in allocation of the manager's budget between law enforcement and monitoring, at the default model values in *SI Appendix*, Table S1, as the penalty for noncompliance varies. The HCR is a fixed proportional harvesting mortality of 0.07. (*A*) The change in the manager's budget allocation to law enforcement, and the household's consequent change in allocation of labor to harvesting rather than agriculture. As the penalty gets higher, the manager is able to allocate less to law enforcement. (*B*) The amount actually harvested and the HCR ("Informed Actual" and "Informed HCR"), when the manager allocates resources to law enforcement to keep illegal harvests within 10% of the HCR. Actual harvest and the HCR become closer as the penalty increases and the manager can better control illegal harvesting. The harvest rates are also shown in the absence of household decisions (when HCR implementation is perfect—"No household actual") and when the manager fails to take account of household decisions (when the actual harvest "Ignored actual" is far higher than the HCR "Ignored HCR"); in both these cases, no resources are allocated to law enforcement.

vesting by the household drops as the penalty increases. Because the manager is concerned with long-term utility maximization, while the harvester is concerned with short-run utility, this strategy means that the harvester is not harvesting as much as they would like. The manager imposes costs on the household in the form of penalties for overharvesting, which are offset by the benefit of a larger resource stock, but have the effect of shifting labor allocation away from harvesting.

Discussion

Management Strategy Evaluation is a flexible framework for modeling the entire natural resource management system, rather than just the resource stock, which has shown its potential to improve fisheries management (16, 17). Even in commercial fisheries, where user motivations are more clearly profit-driven, explicit modeling of their behavior within an MSE framework can improve understanding and prediction of their responses to policy interventions. For example, it can elucidate the processes underlying effort displacement and shifts in target species after spatial closures or changes in gear-based rules (7).

The simulation framework used in MSE precludes analytical solution and so it may lack generality, but it also gives flexibility to incorporate key interactions and model components, particularly related to uncertainty. In this paper, I have extended the MSE framework to include an operating model for harvester behavior, and have shown that this addition brings new dimensions to the approach, which make it much more relevant to terrestrial conservation and to artisanal fisheries. All aspects of this demonstration model are unrealistically simplistic, and it is not parameterized to a particular system. There are an infinite number of potential specifications for each submodel, which need to be chosen with real systems in mind. For example, the biological operating model might include age or spatial structure and a more realistic incorporation of stochasticity into population dynamics, whereas the household model would be more appropriately specified as a full income model so that tradeoffs in household labor allocations could be realistically incorporated (18). However, the aim here is to show how the MSE model framework can be extended to include harvesters and to highlight interesting properties of an integrated model compared with a standard equivalent; for this purpose, a simple specification is most appropriate.

One of the most exciting aspects of incorporating a household OM into an MSE is that it reveals synergies between parallel research fields. In particular, household utility models are highly sophisticated and have been used in terrestrial systems to model the effect of a range of management interventions on natural resource use (e.g., ref. 11). Combining these insights with an MSE approach would benefit both disciplines. For example, the model developed here highlights the key role of relative and absolute returns to labor in determining the sustainability of harvesting, which is well known in the development economics literature but has not been considered from the perspective of the natural resource manager. In fisheries, the focus has tended to be on the scale parameter—the catchability coefficient—when considering the relationship between effort and output, rather than on the elasticity parameter—returns to labor—which may have very different effects in the model. This model also highlights the importance of market access in determining the outcome and stability of harvesting; this result has been theoretically demonstrated in a seminal paper by Muller and Albers (19). However, in previous applications of household utility models to conservation and resource harvesting, households have either been assumed to profit-maximize like firms (e.g., refs. 9 and 20), which may often not be a realistic assumption, or assumptions concerning allocation of productive activity to consumption vs. sale have been relatively arbitrary (e.g., ref. 13). The assumption made about market access for products and labor is in fact crucial to model predictions (18, 19).

One innovation in this model has been the inclusion of a monitoring tradeoff for the manager. This addition illustrates the fact that MSE has far more to offer than just assessing the direct effects of HCRs on stock dynamics. Instead, a wide range of the policy levers open to managers can be evaluated for their effect on system performance. These levers might include increasing the returns to labor on the alternative livelihood, direct or conditional livelihood subsidies, or investment in law enforcement as considered here. As managers focus more on incentive-based interventions such as payments for ecosystem services or individual transferable quotas (21, 22), the ability to incorporate these levers into an MSE is an important step forward. The model also permits, although does not explore, manager learning through investment in reducing observation error, which is an important issue that deserves further study (23, 24). MSE is philosophically aligned with adaptive management; both emphasize learning about the system, explicitly considering uncertainty, and updating models with new information (2, 25). Adaptive management has to date mostly been considered in terms of real-world experimentation, but the virtual experimentation of MSE is complementary.

In fisheries, current progress on MSEs includes the development of multispecies and spatially explicit operating models and their use in ecosystem-based management (2, 26). The need for improvement of the implementation model is well recognized, as is the urgent need to better incorporate economics into the models, but to date there has been very little progress compared with the growing sophistication of the operating models (1, 12). The extension of the MSE framework so as routinely to include a harvester OM would encourage the development of these aspects and ensure that MSE has a less top-down flavor; at the moment it is seen as providing advice to help managers in their decision making, which undersells the value of the approach. By modeling the system as a whole, it is just as possible to use the MSE approach from the perspective of the resource user; taking this perspective may further enhance stakeholder engagement, which has been an important feature of real-world implementation of MSEs to date (16, 17). The one major study that has included a detailed, empirically based socioeconomic component in an MSE highlighted the sensitivity of model results to harvester behavior and called for further work in this area (7).

The addition of a harvester OM highlights the fact that there are two active sets of participants in the system, both of which face constraints and uncertainties and have a limited set of actions that they can use to influence the system. It also widens the range of potential performance metrics to encompass the utility of the resource user, which has resonance with the ecosystem services approach and the recognition that natural resources should be managed for the welfare of their users, rather than with the users seen as the problem; this change in attitude has been particularly obvious in recent conservation discourse, but it is also prevalent in the literature on artisanal fisheries management (27, 28). This shift also implies that managers need to collect data not just on the biology of and trends in the exploited stock, but also on household livelihoods and the tradeoffs and constraints that resource users experience.

The MSE approach was a major innovation in fisheries management, with its emphasis on structural and observation uncertainty, and on treating managers as part of the system rather than external observers (15). Its emphasis on producing robust decision rules that managers can actually implement, rather than on optimization, was also an important contribution. Now that there is empirical evidence of MSEs enhancing fisheries management worldwide (1, 26), the time is ripe for this technique to be applied to other fields of resource management. There has been one recent application of the approach to pest management (29), and conservationists are starting to consider how best to apply it to their systems (30). Any system in which there is an actual or potential linkage between managers making observations of a resource and those observations contributing to management action is a potential target for an MSE approach, which potentially encompasses all exploited resources. The model framework presented here demonstrates how the approach can be extended to include the decision making of the resource user, which is an important step in translating this potential into actual application. The next necessary step is to build an integrated MSE for a real-world terrestrial conservation system.

Materials and Methods

Because the exploration of biological complexity is not the aim of this study, I used a simple stochastic discrete time logistic population model for the resource OM. For the harvester OM, I used a simplifed version of the household decision model of Damania et al. (13). The household maximized its utility subject to a budget and a labor constraint, based on the productivity of labor as allocated to either farming or wildlife harvesting.

The variable inputs to the harvester OM were the resource stock size (from the resource OM), the probability of detection of illegal harvesting (from the monitoring model), and the legal harvest limit (from the assessment model). The output from the model was the actual harvest rate, which fed into the resource OM in the next time step. The manager could influence the harvester's effort only by altering the cost of harvesting above the legal limit set in the HCR via allocation of the management budget to law enforcement. I assumed the penalty for illegal harvesting was externally set, which is realistic in most conservation situations. I also assumed that the revenues obtained from penalties were not fed back into management and, hence, did not impinge on manager decision making.

The harvest control rule was not the main focus of the model, and so only three simple HCRs were tested: "Static," which was a simple proportional harvest rate; "yield maximizing," in which the assessment model chose in advance the harvest rate that it anticipated would produce the maximum yield over the assessment period; and "utility maximizing," in which the assessment model chose in advance the harvest rate that it anticipated would produce the maximum utility to the harvester over the assessment period.

The manager had a fixed budget to allocate between monitoring the resource population to reduce observation uncertainty and monitoring the users to deter illegal harvest (Fig. 1 *Lower*). The effectiveness of both the resource monitoring and harvester monitoring increased nonlinearly with spend. Two rules for allocation of monitoring effort were tested: Static, in which the allocation split was constant, and "Informed", in which the manager performed a model-based assessment of the optimal allocation in advance. They used the following performance rule: Maximize the allocation of resources to population monitoring, subject to illegal harvesting representing no more than 10% of the HCR. This rule meant that the manager set the allocation to law enforcement at a level just adequate to reduce harvesting to an acceptable level—zero if there was no prospect of illegal harvesting occurring and 1 if illegal harvesting could not controlled.

Management objectives were to ensure resource conservation and maximize yield, and ensure utility remained consistently high. Performance of the HCR against these objectives was assessed by using three performance metrics: the proportion of years in which the population size was <30% of carrying capacity, the average annual harvest in the reporting period, and the proportion of years in the reporting period in which utility was <50% of the maximum utility for that run. Please see the *SI Appendix* for further details of the model.

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