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Integrating Management, Research, and Monitoring: Balancing the 3-Legged Stool

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Research and monitoring programs are often thought of as competing with "on the ground management" for attention and funding. This is false trichotomy; instead, it is more appropriate to view management, research, and monitoring as complementary endeavors, in which loss of any 1 of the 3 is disruptive to the remaining 2. There is often significant or even profound uncertainty about the system's likely response to management, beyond environmental and other sources of uncontrolled variation. Sometimes this uncertainty can be reduced through directed research studies, including experimentation. However, management decisions usually cannot await the completion of elaborate, multiple-year studies. Adaptive resource management (ARM) provides managers a way to make optimal decisions with respect to resource objectives, given the current level of uncertainty about system response, *and in anticipation that learning will improve decision-making through time*. Under ARM, resource goals and objectives are *always* paramount and research and monitoring programs exist to provide managers with the tools they need to make better decisions. The essentials of ARM are clear, compelling, and critically needed in natural resource management. We can no longer afford the luxury, if we ever could, of management divorced from research and monitoring, and vice versa. By keeping the focus on management decision-making and resource objective outcomes, ARM places an explicit value on research and monitoring that then can be used to justify monitoring and research programs.

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Introduction

In our experience in working with natural resource managers and researches, we often encounter situations where management, research, and monitoring activities are viewed distinctly. Management is typically viewed as involving the concrete, hands-on, practical aspects of conservation: preserving and managing habitats, regulating harvest and trade, and other aspects of "on-the-ground" work. Research, although recognized as important, is often viewed as less important than monitoring, and certainly than management-somewhat as a luxury of academia that we should do, but only if we have sufficient time and funding left. Monitoring is viewed as a way of assessing the status of populations, communities, and ecosystems, but typically is not formally connected to conservation decisions.

Here we argue that management, research, and monitoring are actually complementary, not competitive activities, all 3 are important to successful conservation, and loss of any 1 of the 3 disrupts the other 2. We use the metaphor of a 3-legged stool to convey these ideas.

Management As Modeling

Management is simply taking an action to obtain some desired resource outcome. It requires a range of alternative actions that can be taken, and specification of an objective that we are trying to achieve. Examples of management include: the application of prescribed fire to increase or improve habitats and, presumably, sustain larger populations; the setting of harvest regulations to provide recreation, control populations that may be damaging habitats or otherwise causing problems, and to providing eco-

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nomic benefits; the construction of reserves to maintain species diversity, protect endemics, and/or provide corridors of movement among discrete habitats or populations.

Research is a process of inquiry that includes description of natural systems, but also involves addressing questions about how these systems function. Thus, research would include testing and quantifying ecosystem feedback relationships and mechanisms of population regulation, to name two. *Monitoring* involves the observation of natural systems through space and over time, and may be descriptive (i.e., simply oriented toward quantifying patterns or trends), but may also be connected directly to research (by providing answers to testable predictions) or management (by providing feedback about the results of management actions).

As we discuss below, we view management, research, and monitoring as highly complementary activities, whose boundaries are often blurry. However, there are unifying ideas, and one of these is the idea of a model. Conservation managers usually do not think of themselves as modelers. However, even if managers are not conscious of the fact, every management action involves a decision that is made to reach a goal, and at least implicitly involves a model. For example, a manager may desire to increase carrying capacity via habitat modification such as prescribed fire. Implicitly, he or she believes that certain actions (e.g., a burn) are likely to have the desired results (habitat improvement), and these outcomes are more desirable (have higher objective value; Figure 1a). This belief is a conceptual model of how the system is likely to respond to management, whether or not it is formalized into a mathematical model.

Uncertainty In Management

Sources Of Uncertainty

The reality is that uncertainty nearly always confounds a simple decision model (such as Figure 1). That is, the manager can never be sure with 100% certainty that any given decision will result in the desired outcome. Management uncertainty comes in 4 basic types: environmental uncertainty, partial controllability, partial observability, and structural uncertainty; we emphasize the last.

One basic but important form of uncertainty is that due to the fact that habitat and populations are influenced by factors that may not be under management control. For example, if we decide to burn a woodland to improve habitat conditions, a disease outbreak or unusually severe winter may occur that results in a lower than predicted population response. Likewise, even if we don't burn, other favorable factors may cause the population to perform better than predicted. The influence of factors in the environment that are unpredictable, and that add to the influence of our management decisions, is termed *environmental uncertainty*. A similar result can occur because the management itself is only partially controllable, for instance, a burn may be cooler or less extensive than planned, resulting in a poor response by the population. This is referred to as *partial controllability* (Figure 1b).

In addition to these 'real' sources of uncertainty, monitoring programs generally will not be able to perfectly measure the systems response to our management. Especially when we are monitoring abundance and other population or community attributes, these will usually be based on some type of statistical sample, and thus subject to error. This is referred to as *partial observability*, or sometimes, statistical uncertainty (Figure 1c).

Finally, in addition to all the above sources of uncertainty, we return to an idea we started with, namely that management implicitly involves acting under a model of how our system is likely to respond to management. This model contains, at least implicitly, current knowledge as to how the system functions, which is presumably based on past observation and research. However, this past knowledge basis is seldom unequivocal, and is often very incomplete. Unless we are absolutely certain about the basic mechanisms that determine our system, we should be honest and admit that this model is but one hypothesis about how the system works, and that it may not be the best model. In the prescribed fire example, model 1 is that burning provides a ben-

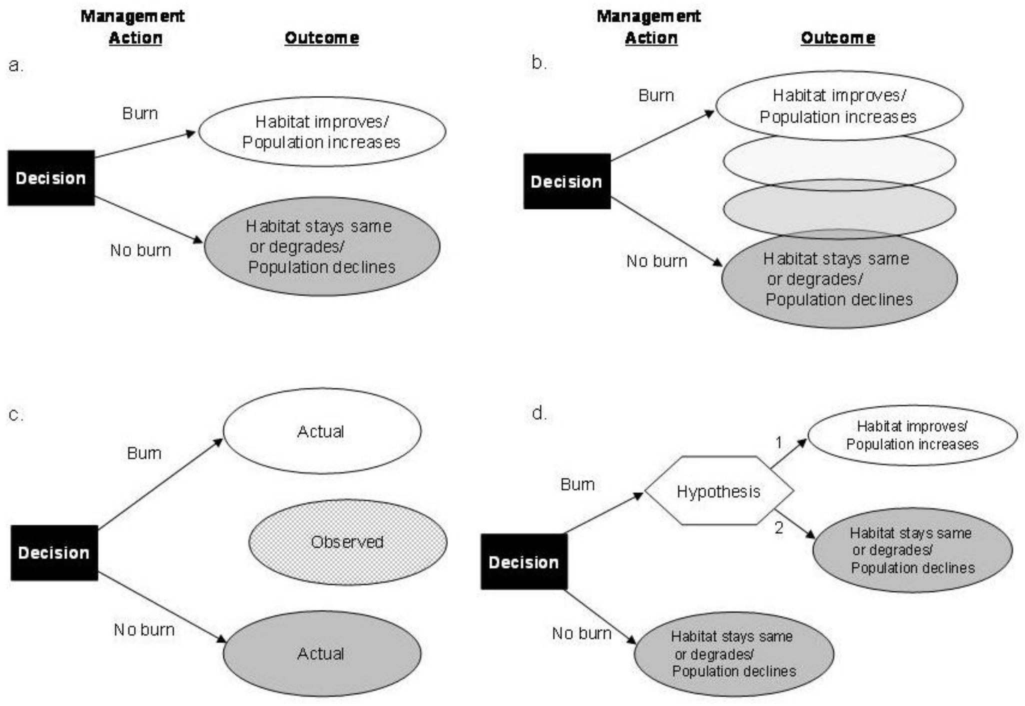

Figure 1: Schematic of a hypothetical decision model for effects of prescribed fire on habitat and population response with (a) no uncertainty in decision-outcome, (b) environmental uncertainty, (c) partial observability, and (d) structural uncertainty. Here objective values could include the number of hectares of good habitat and/or population size.

eficial impact, but we should at least consider the possibility that model 2 (no discernible impact) is correct. We refer to this last source of uncertainty as *structural uncertainty*. Seen in this light, structural uncertainty is both a research issue-it occurs because our system understanding is imperfect-and a management issue-resolving or reducing it leads to better decision making.

Dealing With Uncertainty In Decision-making

We begin with the recognition that, although there are several possible ways of dealing with uncertainty, ignoring uncertainty can have severe consequences. Failing to deal with uncertainty may lead to a false sense of security in decision-making and ultimately compromises our ability to reach our conservation objectives. We favor the approach of incorporating uncertainty into the objective by means of *expected values*. Expected values are simply a form of weighted averaging, in which objective values under different possible decision-outcomes are weighted according to the probability that each outcome occurs. The decision-maker than selects the decision that results in the best (e.g., maximum) objective value on *average*, which is the expected value. One important implication of this approach is that reducing uncertainty– if it can be done– has measurable value in terms of the conservation objective. In fact, it is possible to calculate how much improvement could be made in decision-making, were it possible to completely eliminate uncertainty; this is known as the *expected value of perfect information* (Lindley 1985, Clemen 1996) in decision-making.

Reducing Structural Uncertainty

Some types of uncertainty, such as environmental uncertainty, are essentially impossible to control. These must be considered in decision-making, but in all likelihood cannot be reduced (unless we consider artificially controlling the range of environmental variation, e.g., via water control devices). Others can be at least partially reduced by concerted effort: e.g., better field techniques may reduce (but likely not eliminate) partial controllability and better survey methods may reduce partial observability.

We devote special attention to structural uncertainty, because it is the one source of uncertainty that 1) is very frequently ignored, and 2) can be reduced through time via an adaptive approach. Before discussing adaptive approaches, we mention the two other major approaches that can be used to reduce structural uncertainty, because readers are likely more familiar with these approaches, they have occurred more frequently in the literature, and they continue to have merit.

Experiments - which we define as involving control, randomization, and replication of independent subjects - are the "gold standard" of scientific inquiry. Experiments clearly are ideally capable of reducing uncertainty very quickly, and thus are attractive. However, realistic experiments at any meaningful spatial scale are difficult or impossible to conduct in most conservation systems. In addition, because experiments are directed at scientific hypotheses, rather than management objectives, they are not necessarily efficient means of reducing uncertainty for decision-making.

In contrast to experiments, *retrospective studies* are based on an examination of patterns in data that have been collected in the past; thus they are analyzed "retrospectively." These often can provide a good initial basis for the construction of alternative hypotheses and predictive models used in conservation. However, potential explanatory relationships are actually correlative, because of the lack of controls, and are typically confounded with other factors. As a typical example, Conroy et al. (2002) retrospectively investigated the potential influence of habitat, hunting, and competition with mallards (*Anas rubribes*) on populations of American black ducks (*Anas rubripes*). They detected evidence for the impacts of all three factors, but could not infer causation because of confounding (e.g., habitat declined and mallard competition increased over the same period). Conroy et al. (2002) were able to construct predictive models, but other approaches such as experimentation (Anderson et al. 1987) or adaptive resource management (below) are required to reduce structural uncertainty for this problem.

Without denying the importance of both experimentation and retrospective analysis, we advocate a third approach, called adaptive resource management (ARM; Walters 1986), as being generally more suited to conservation decision-making. We especially like the ARM approach because it fits nicely with the idea of multiple working hypotheses (Chamberlin 1897), which we advocate instead of null hypothesis testing. ARM can be implemented in virtually any resource system, and has the advantage of being directed at meeting the conservation objective, not at meeting a scientific objective per se. In fact as we will elaborate below, conducted properly, ARM involves no tradeoff whatever in meeting the resource objective, and thus would appear to be the optimal means of incorporating information into decision-making and reducing uncertainty. Below we lay out the principal elements of ARM, provide some simple examples, and address some common myths and misunderstandings that have contributed to the (so far) relatively rare use of ARM in practical conservation.

Elements Of Adaptive Management

ARM consists of 3 essential components. The first is explicit predictions of the effect of management actions on resource objectives (e.g., population size, harvest) under 2 or more models. These provide the means for comparing the relative support for different management actions. Here, structural uncertainty is expressed in the form of alternative models (e.g., hypotheses) of system dynamics (Fig-

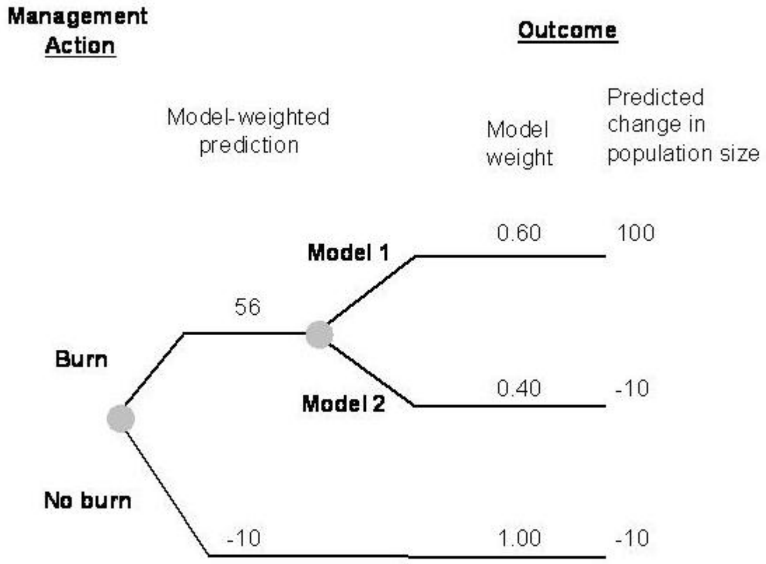

Figure 2: Schematic of a hypothetical decision model of the effects of prescribed fire decision on population response with 2 alternative models. Model 1 predicts an increase in population of 100 in response to burning, whereas model 2 predicts a decrease of 10. Using the model weights shown, the model averaged prediction of population response to burning would be an increase of: 100×0.6 + -10×0.4 = 56.

ure 1d). The set of models should be only as large as is necessary to include the biologically plausible representations of system dynamics. During each decision opportunity, predictions are made under each alternative model, weighted by the relative support for the model, and combined across models (Figure 2). Decisions then are made based on comparing the model-averaged predictions associated with each management action. Although model weights change as information is accrued (more below), the assignment of initial model weights is relatively flexible and can be based on retrospective analyses, expert judgment, or assigned equally among models.

Sequential decision-making is another requirement of ARM and is frequently encountered in natural resource management. Sequential decision-making involves tracking a resource (e.g., population, habitat condition) through time and making decisions based, in part, on the observed status of the resource (Figure 3). The set of management objectives and actions are usually constant, so that the same (or similar) decisions are continuously revisited. Sequential decision-making need not take place on an annual basis and can occur in space as well as in time (Figure 3). The former is particularly useful in situations where decisions will not be revisited at a particular site on a short time horizon but are made over a number of sites. Information feedback, in this sense, is used to improve future decisions at sites that have yet to be managed. Regardless of whether sequential decision-making is through space or time, the key is to provide feedback on the effects of management actions in a timely manner to improve future decision-making.

Monitoring is the third required component of ARM. It provides the information that is used to resolve the key uncertainties - chiefly, structural uncertainty. As described above, structural uncertainty is expressed quantitatively as model weights or relative evidences supporting each model, which can be viewed as probabilities that each respective hypothesis best represents “truth”. To resolve this uncertainty, we need to determine which model best approximates the system dynamics and update the

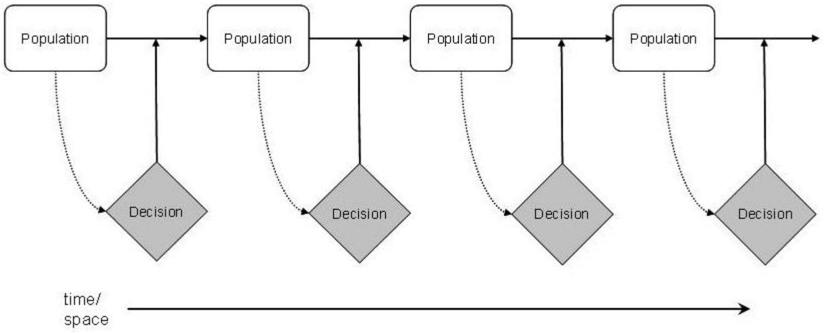

Figure 3: A graphic representation of a sequential decision-making process, through time or space, with population as the resource of interest.

weights to reflect our newfound knowledge. Operationally, this is accomplished by comparing model predictions to subsequent observations of the status of the resource (e.g., population size). Thus at a minimum, monitoring must include a measure of the status of the resource that is consistent with prediction (e.g., if population size is predicted, population size must be measured). The prediction that more closely matches the observed status results in a higher likelihood value and a corresponding increase in the weight for that model. This new weight then is used to estimate the model-averaged predictions for comparing alternative actions at the next decision time. Thus, prediction, management, and monitoring are all connected in a closed loop (Figure 4). In addition to structural uncertainty, the additional sources of uncertainty due to partial observability, partial controllability, and environmental uncertainty, must also be accounted for in the decision model. The general approach is to use probability modeling to account for these factors, either implicitly or explicitly. This is important, both because it gives a more honest picture of the rates of learning under ARM, and helps to direct research and monitoring priorities to reducing uncertainty, where feasible.

ARM: Myths And Misunderstanding

Although ARM appears to be a useful approach to managing gamebirds, to our knowledge, ARM has only been formally applied to waterfowl harvest decision-making (Johnson and Williams 1999). The failure to implement ARM is may be due to institutional resistance (Samson and Knopf 2001), but we think it is also attributable to widespread misconceptions concerning the nature of ARM. Perhaps the most common misunderstanding is that ARM is research. ARM is first and foremost *management*. The primary objective of ARM is to make the best decision with respect to management objectives. Learning occurs as a byproduct of management rather than experimentation. In fact, experimentation (a.k.a. probing the system) can be suboptimal because the system can be driven to a state that is undesirable, potentially reducing future returns (Williams et al. 2002). For example, experimental burning may cause the system to revert to a vegetational community that does not support gamebird populations. In ARM, the goal of learning is to reduce the uncertainty that has the greatest direct impact on decision-making. Thus, learning is targeted on those key components that result in improved decision-making and presumably, greater resource gains.

Another common ARM myth is that it is too risky. We contend that natural resource decision-

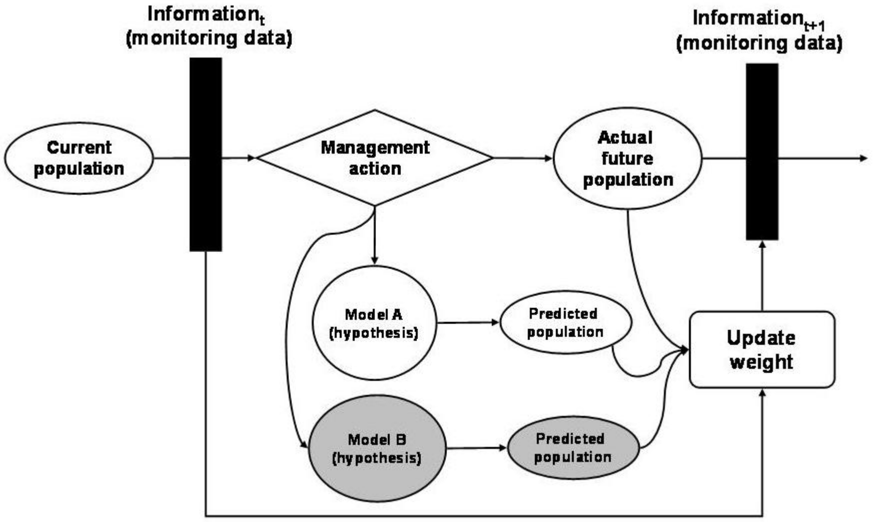

Figure 4: Components of adaptive resource management include: prediction under alternative structural models; feedback of monitoring information to updating weight on alternative models; and adaptive updating through space or time.

making is inherently risky. As we discussed earlier, decision-making is fraught with uncertainty. Hence, all management actions (or inactions) can have unintended and unanticipated consequences. Uncertainty can be reduced by the acquisition of greater knowledge through study and experimentation, which can take considerable time and as discussed above, can force a system into an undesirable state. Management decisions, however, often cannot be delayed until sufficient knowledge has been acquired. Given that decisions under greater uncertainty are riskier than those under less uncertainty, procedures that reduce uncertainty also reduce risk. ARM reduces uncertainty through management and thereby reduces risk. Further, ARM is always directed at achieving the resource goals. Thus, any reduction in uncertainty is not at the expense of, but in addition to, resource gains.

Beliefs that ARM is costly and complicated also are unfounded. Most agencies currently perform most of the tasks required for ARM and hence, ARM would not require additional expenditures. For example, choosing and implementing management actions, monitoring, and sometimes modeling expected outcomes are common practices. All that is then required is a formal means of integrating these components. This integration does not need to be complicated and can be completed with available user-friendly software, such as Netica (Norsys Software Corp., Vancouver, BC, Canada). In fact, the use of simple (but useful) models is preferable in ARM (Williams et al. 2002). Additionally, the evaluation of the sources of uncertainty during the ARM model development is useful for prioritizing and focusing monitoring efforts on only those factors that matter, which can translate into greater cost efficiency.

Unbalancing The Stool

In an era of shrinking budgets and increasing expenses, managers are often faced with decisions on how to cut costs. Unfortunately, one common response is to eliminate what are believed nonessential programmatic elements. We argue that management, research, and monitoring are *all* crucial for natural resource conservation and that the loss on any one of these elements reduces the effectiveness of the others. The elimination of research often results in stagnation, where new scientific hypotheses/ ideas do not become part of management. This also perpetuates a false separation of "management" from "science," thereby reducing the effectiveness of the former and eliminating the context for the latter. Similarly, the elimination of monitoring reduces the effectiveness of management because decision makers no longer have a basis for judging how system is performing in relation to management objectives. Without the feedback provided by monitoring, there is no ability to assess model predictions with data, which eliminates the potential for learning about how systems operate. By contrast, the example of ARM for the management of North American waterfowl exemplifies how management, research, and monitoring can be integrated to form effective, scientifically based decision-making.

When active management is eliminated, decisions are then made by default rather than directed toward an objective. In this context, research and monitoring programs no longer have explicit value. Learning may still occur passively if monitoring continues, but progress would be considerably slower. However, if monitoring also is eliminated (e.g., if animals are no longer harvested, then tag recoveries will no longer be available for survival estimation), learning is prevented.

Summary

Management, research, and monitoring programs are appropriately viewed as mutually supportive of conservation goals, where the loss of any 1 of the 3 is disruptive to the remaining 2. Management explicitly includes the goals of the decision maker and other stakeholders in evaluating the possible consequences of any potential action. Research allows us to state the possible consequences of management actions as predictions, which can be then be used to compare alternatives and select one that leads to a decision that appears most likely (taking into account uncertainty) to achieve our goals. Monitoring provides us with information about the state of the resource system, so we can judge whether we are approaching or diverging from our stated goals, as well as information feedback that allows us to test the predictions of our decision models, and reduce uncertainty through time. This "closed loop" process, known as ARM, formally integrates management, research, and monitoring for more effective natural resource decision-making. ARM provides a mechanism for dealing with uncertainty - inevitable in conservation decision-making - while always keeping resource goals and objectives as paramount. Under ARM, research and monitoring programs have explicit value in terms of the resource objectives are clear, compelling, and critically needed in natural resource management.

We view all 3 of these legs - management, research, and monitoring - as essential to sound conservation. Removal of any 1 of the legs is disruptive to conservation, and ultimately counterproductive. In particular, action-oriented management is sometimes pitted against research and monitoring in the competition for limited funds. This sets up a false choice, a bit like asking whether children need food or education in order to become productive adults. In contrast, under ARM, research and monitoring have explicit value for their contributions to decision-making. Conversely, we "learn by doing," with management actions providing the grist for the testing of critical assumptions, ultimately reducing uncertainty and improving decision-making.

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