What Can Adaptive Management Do for Our Fish, Forests, Food, and Biodiversity?

ANA M. PARMA AND NCEAS WORKING GROUP ON POPULATION MANAGEMENT

Society invests heavily in science and research aimed at providing guidance on how to manage biological resources, yet the world is filled with too many management failures. Why is this? One reason is that the task itself is so difficult—the environment varies, we never really know the underlying processes that drive population change, and observation errors can be very large when we study populations in the wild. But worse than uncertainty itself is the fact that we tend to underestimate uncertainty. We place too much confidence in our assessment and forecasting models. Fisheries, conservation, and pest control have much to gain by embracing so-called adaptive management. Adaptive management forces us to acknowledge uncertainty, and to follow a plan by which decisions are modified as we learn by doing. Indeed, we can expect little more than continued failures if adaptive management is not adopted in a determined and widespread fashion.

KEY WORDS: adaptive management, learning strategy, uncertainty

In *Independence Day*,* we earthlings are invaded by outer-space aliens thirsty for planet Earth's resources. Society, confronted with this ultimate resource management crisis, resorts to an MIT-trained scientist, who comes up with a slick alien-control plan, rallies managers behind him, and solves the riddle by the sheer power of science and technology.

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Less spectacular cases of fisheries, forestry, and wildlife management, however, contradict the myths—both popular and academic—that deify the power and influence of scientific expertise. In the real world, mismanagement of biological resources has been common and well publicized,[1–4] and has occurred in spite of substantial investment in science and research. Why is this? Although economical and political factors are major contributors to these failures,[5] the limits of our ability to predict the response of ecosystems to human interventions have certainly also had an important role. This is most obvious in the cases in which management disasters can be traced to seriously flawed assessments and forecasts.[6] But short of such extremes, uncertainty always weakens scientific advice, easing the way for political and economical shortsightedness to neglect the science in favor of special interests. Because the credibility and perceived usefulness of science are at stake, uncertainty tends to go understated when expert advice is communicated to the resource managers. Managers, in turn, often find it difficult to interpret uncertainty and expect more precision from science than science is able to deliver.

Biological and physical processes have inherently fluctuating components that will never be fully explained, predicted, or controlled. Finally, between us and any biological system there is an observation process that is fragmentary and prone to error. As a result, knowledge is and always will be incomplete, regardless of the effort spent trying to refine it. But we still have to act using whatever information we have at hand, no matter how limited. For example:

- A farmer has to decide whether or not to spray a crop before full information about the density of pests and natural enemies is available.
- The level of harvest for a newly developed fishery needs to be determined without knowledge of either the abundance of the stock or how reducing the size of the reproductive population may affect the subsequent number of fish recruiting into the stock.
- A tract of forest is overgrown and susceptible to a potentially ravaging fire. An environmental agency

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[*]Independence Day, directed by Roland Emmerich, Twentieth Century Fox, 1996.

needs to decide if the forest should experience a controlled burn, and if so, how much area should be burned, without precise knowledge about how fuel load influences the probability and intensity of a natural fire.
- An agency must decide whether or not to capture individuals of an endangered species for captive breeding with limited knowledge about population size and actual threats to the species, and great uncertainty about the likely success of captive breeding and reintroduction.

In each case, actions could obviously benefit if more information were at hand. However, decisions cannot wait until such information becomes available: delaying action is itself a management decision with an associated cost. For example, delays in action may fail to prevent a pest outbreak or cause the fishing communities depending upon harvest to experience economic hardship, or lead to a much larger fire occurring spontaneously, or cause the species that is a candidate for captive breeding to go extinct.

Adaptive management has been proposed as a method for ecological intervention in the fact of uncertainty.[7] Although its origins are as old as risk itself,[8] it experienced a resurgence and revitalization in the 1970s and 1980s.[9–11] Indeed, adaptive management is now a buzzword, commonly confused with an ad hoc trial and error approach to management under uncertainty as in"action first, science later."

In this article we attempt to clarify what adaptive management really is and what it can do for biological resource management. We start by characterizing the different forms of uncertainty that plague natural systems, describe how adaptive management proceeds in the face of those uncertainties, and indicate the consequences of not acting adaptively. We point to major problem areas in population control for which opportunities are missed by not pursuing adaptive management. We also discuss some of the intrinsic limitations of adaptive management that have prevented its implementation.

UNCERTAINTY HAS MULTIPLE SOURCES

Several sources of uncertainty conspire against our ability to predict the responses of natural systems to human actions:

- *Process uncertainty*. Natural processes are inherently variable. No matter how good our models may be in describing the rules that govern the behavior of a natural population, we cannot expect these models to predict the exact state of the system at any given time in the future. The future will, at best, be described in probabilistic terms. Consider, for example, the fate of a pest population that has been sprayed with a pesticide. A careful laboratory experiment is conducted and tells us that the probability that an individual will die when exposed to this pesticide is exactly 0.5. Still, we cannot *predict* from this information what fraction of the pest population will be killed by the spraying. The best we can do is calculate the probabilities of obtaining different outcomes, say from killing all the individuals to all of them surviving the spray (Fig. 1a).

Indeed, adaptive management is now a buzzword, commonly confused with an ad hoc trial and error approach to management under uncertainty, as in "action first, science later."

- *Model uncertainty.* In reality, we can never fully specify how nature operates, and so a second source of uncertainty is our own ignorance about the behavior of the system. We can expand the pest control example to illustrate the concept of model uncertainty. In particular, we may not know the probability that an individual exposed to the pesticide will die. In that case, we have infinitely many alternative models about how the process may operate in reality, *i.e.*, the probability of dying could take any value between 0 and 1. While process uncertainty cannot be reduced because the variability in nature is beyond control, model uncertainty can be reduced by gathering new information about how the system behaves. For example, we can expose more insects to the pesticide to improve our estimate of its killing rate. The more individuals we test, the more precise our estimates would be, and so the uncertainty in model specification would be reduced (Fig. 1b). If there were no limits to learning, enough experiments would tell us what the true value of the parameter is with sufficient confidence. But there are always limits to how much we can learn in natural systems. Model specification can be much more complex than in the example above, because not only do we not know the values of the key parameters controlling the dynamics, we are usually also uncertain about the actual structure of the model itself (*e.g.*, Are all individuals equally susceptible to the chemical? How is the toxicity of the pesticide affected by weather and soil conditions? How does efficacy relate to dosage?). In population modeling one could argue that detailed knowledge of birth, death, immigration, and emigration—and the factors that affect them—should allow us to predict the long-term consequences of any management action. Of course, we never have all that information. Consequently, our data on the behavior of biological systems are usually consistent with several competing hypotheses, each of which may dictate very different"best"management options.
- *Observation uncertainty.* In most cases, the biggest impediment to

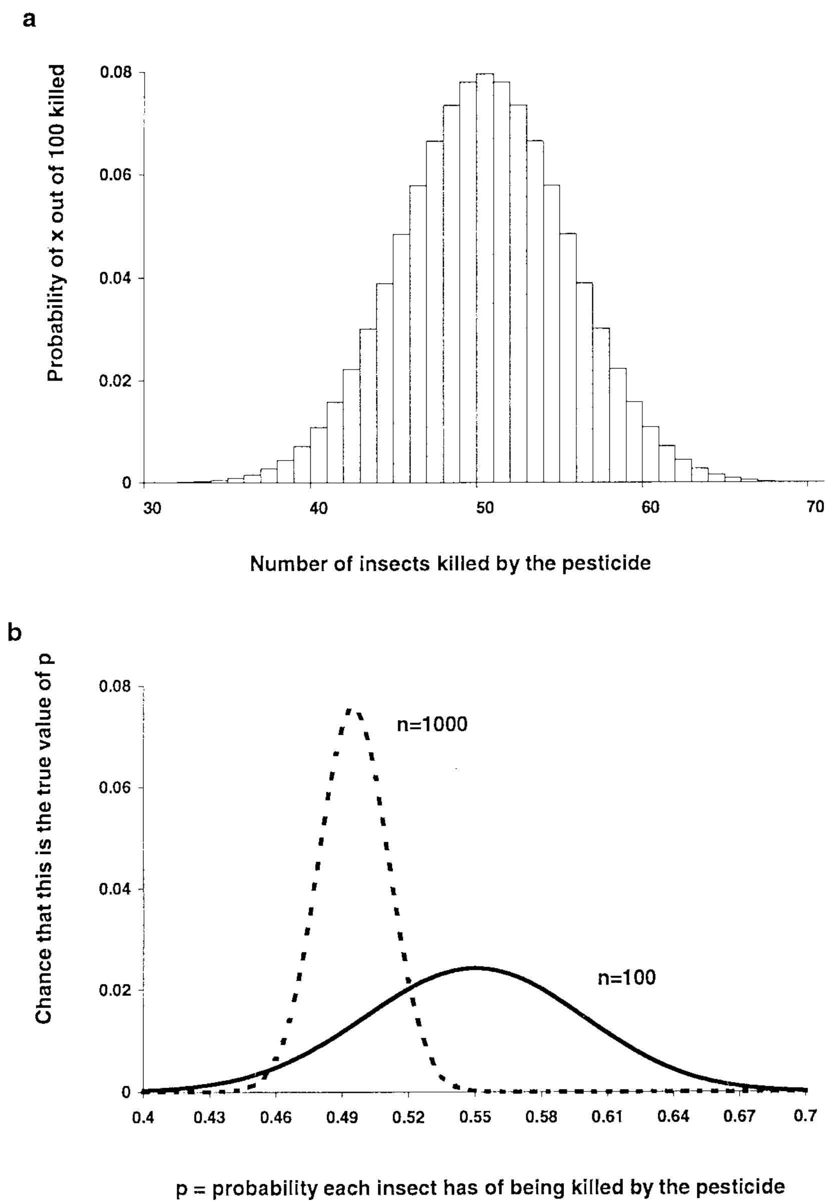

Figure 1. **a:** A population of pest insects is sprayed with a pesticide that is 50% effective. Even if we know that each individual has a 0.5 chance of being killed, we cannot predict the exact outcome except in terms of a probability distribution. For example, we show the probability that x individuals over 100 survive the spraying. **b:** More realistically, we would not know the exact probability each individual has of being killed, but we can do an experiment to estimate it.[34] If 55 individuals out of n =100 exposed survive a trial, the true survival probability could have different values consistent with that outcome, the most likely being 0.55. Model uncertainty, as represented by the width of the bell-shaped curve, is reduced by increasing the number of insects sprayed, say to n = 1000. Learning also involves both moving the peak of the curve as more information is obtained.

learning is the fact that between us and any natural system there is an observation process that also introduces uncertainty. We do not observe our managed populations directly, nor do we observe all of the relevant variables. Rather, we follow the monitoring protocols to sample or measure periodically a subset of population attributes, and from those measures we try to reconstruct the actual state of nature. Data are usually limited and highly variable, and so observation uncertainty is typically substantial. For example, errors in fishery stock assessments exceeding 30% are not uncommon, even when no major problems in the assessment techniques have been identified. Moreover, our data and assessment methods may be flawed, and when that has happened errors in stock assessment as large as 200% have been detected.[6]

Learning about how the system behaves is further complicated by the fact that dynamic processes are generally *nonlinear*. Nonlinearity means that the rates at which variables of interest change in response to changes in predictor variables are not constant, but depend on the status of the system. For example, the birth rate and juvenile survival in a harvested population often vary so nonlinearly as a function of the population density that the relationship between the size of the reproductive population and the number of juveniles is positive over some stock sizes and negative over other stock sizes (Fig. 2). Nonlinearity implies that we cannot extrapolate the behavior observed from a narrow range of population densities to how the system would behave if the population increased or decreased beyond that range. Suppose the points in Figure 2 corresponded to pairs of observations on population size and number of recruits. These observations would be consistent with different hypotheses about how recruitment is influenced by population density. In particular, the number of recruits per unit of reproductive population may increase or decrease as the population decreases, depending on the nonlinear form of density dependence. There is, in fact, an infinite range of possible shapes the curve could take, all of them consistent with the available information. The alternative models could not be discriminated without observing the system at states for which the different models clearly predict different responses.

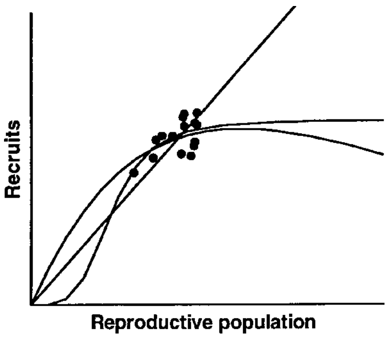

Figure 2. Different models for the relationship between the number of reproductive individuals in a population and subsequent number of recruits (linear and nonlinear) are consistent with the available data (solid circles). The alternative models cannot be discriminated without observing a wider range of population abundance.

WHAT IS ADAPTIVE MANAGEMENT?

Management interventions, whether in harvest, control, or conservation problems, are aimed at achieving some objective(s) and must proceed in the face of all these sources of uncertainty. While basic science may help to narrow the alternative hypotheses about processes that control the system dynamics, *it is mostly through perturbing the system and monitoring responses that we will learn about how nature operates.* But to get the most out of our interventions, we need a plan that 1) recognizes the uncertainty, 2) contemplates monitoring system responses to interventions, and 3) anticipates that future management interventions will be modified as we gather more information and learn about the behavior of the system.

Put as concisely as possible, adaptive management consists of managing according to a plan by which decisions are made and modified as a function of what is known and learned about the system, including information about the effect of previous management actions. The key components of an adaptive management plan are a *management policy*, i.e., a set of rules that specify actions as a function of the existing information about the system status and behavior, a *monitoring plan* to watch system responses, and a *management system* that implements the policy. Management decisions depend on observations about the state of nature. In turn, future observations may be more or less informative about the system behavior depending on the particular actions taken.

The first stage in designing an adaptive management plan is to gather all available information about the system to be managed and to specify *alternative models* that are consistent with that information. Next we design a monitoring plan, i.e., we specify which variables are going to be observed and how, and characterize the uncertainty inherent in the observation process. Finally, we specify possible management *controls* or ways in which we can intervene in the system. For example:

Adaptive management is ecological intervention with a plan for learning about the system.

- In a harvesting problem, a control may be the harvest taken from an animal population in a given season, or the size of a clearcut, or the rotation time in forest management.
- In a pest or vector disease problem, a control may be the level of pesticide to apply, or the number of individuals of a natural enemy to release, and when to release them.
- In a conservation problem, a control may be some form of habitat enhancement designed to protect a critical life history stage of a given population, or a managed burning to maintain an appropriate habitat for a threatened species.

A management policy determines the values of current and future controls as a function of what is known about the system. For example, in a harvesting problem, one such policy may be to harvest a constant fraction of the population as long as total abundance is above a certain threshold.

Before a management plan is implemented, the performance of alternative policies needs to be evaluated in terms of their ability to achieve management goals. This evaluation usually involves specifying trade-offs between expected costs and gains associated with the different candidate policies. When the alternative hypotheses can be summarized as a limited set of options, policy performance is evaluated for each of the possible scenarios. Results of such analyses can be summarized in the form of *decision tables*, which have one entry corresponding to the alternative hypotheses about the state an dynamics of the system, and another entry with the alternative management options.

An example of a decision table constructed for the Serengeti wildebeest (Fig. 3) by Pascual and Hilborn[12] is presented in Table 1. The management goal is to allow some wildebeest harvest without compromising the long-term persistence of the population. Management alternatives correspond to different harvest rates, evaluated in terms of long-term harvest and probabilities of quasiextinction, under three different scenarios about the effect of rainfall on wildebeest reproduction, which is a crucial aspect of wildebeest biology that is not yet resolved. The cells in the table give the payoffs to each of the five management alternatives in the rows, when "nature" behaves according to each of the three scenarios in the columns. The stronger the effect of rainfall on reproduction, the higher the harvest rate that maximizes the long-term catch. However, because risks naturally increase for increasing harvest rates, lower harvest rates may be desirable depending on management goals.

When, as in this example, different views of nature dictate different best actions, the average performance of each policy will depend on the probabilities assigned to the alternative hy-

Figure 3. Each year more than 1 million wildebeest (*Connochaetes taurinus*) initiate their great migration along the Serengeti plains in search of fresh pastures, attracting millions of tourists from all over the world. Due to reduced patrols, poaching in the Serengeti National Park has increased over the last 20 years and ways for regulating exploitation are being considered.[12] How much harvest can be allowed without compromising the long-term persistence of the population? (Photo by Ulrike Hilborn)

TABLE 1. Decision analysis table for the Serengeti wildebeest*

	Effect of rainfall on recruitment		
Harvest rate (%)	**Weak**	**Intermediate**	**Strong**
Long-term harvest (thousands of individuals)			
0	0	0	0
3	87	56	42
6	85	70	62
9	74	73	71
12	66	72	76
Probability of population dropping below 250,000 in 200 years			
0	0	0.01	0.05
3	0.02	0.06	0.11
6	0.1	0.17	0.22
9	0.31	0.32	0.33
12	0.53	0.46	0.45

*Columns show three different hypotheses about how strongly recruitment is affected by rainfall during the dry season. Rows show different levels of harvest (fraction harvested each year). The outcomes are the long-term harvest (upper block) and the probability of quasiextinction below the historical low level of 250,000 individuals in a 200-year horizon (lower block). Future population trajectories were simulated using a stochastic model where both survival and recruitment depend on rainfall. Modified from: Pascual and Hilborn.[12]

potheses. If the three hypotheses about wildebeest reproduction had equal credibility, a harvest rate of 9% would, e.g., result in maximum expected long-term catches on average across the hypotheses. However, such a policy may have unacceptably high risks of driving the population below its historic level.

In this assessment of trade-offs we are treating policies as if they were cast in stone when in fact they are not. Choices made in this way are called *myopic* because they ignore future learning. They would, indeed, be optimal if there were no further monitoring, or if decisions irreversible. If monitoring continues, the probabilities assigned to the alternative hypotheses, and in turn the best choices, will change as we gather more information. For example, new observations may favor the idea that rainfall has only a weak effect on reproduction, and we may decide to lower the harvest rate accordingly. When policies are adapted in response to new information, but learning is not incorporated as a management goal, management is called *passively adaptive*. Trial and error approaches can be viewed as passively adaptive, *if decisions are made as part of a learning strategy.*

But ignorance has a cost, which can be measured by how much we lose by not knowing how nature works in reality. Indeed, if rainfall had a weak effect on wildebeest reproduction, an 18% increase in yield could be achieved by harvesting at 3% instead of 9%, and risks to the population would be reduced. Learning about which hypothesis is correct would improve our ability to achieve management goals. Clearly then, we should choose alternative policies *partly on the basis of their ability to accelerate learning.* Passively adaptive policies may miss the opportunity to learn faster by neglecting the fact that some management actions can be especially informative about the status and biology of natural populations. For example, management policies that tend to stabilize a population around some state considered to be optimal prevent us from learning about potential gains that could be achieved by letting the population grow or drop to a different level; i.e., they prevent us from learning about the validity of the policy.[13] In cases where spatial replication is possible, policies that provide contrasts between different management units will be much more informative about population dynamics, much in the same way as treatment and controls work in research experiments.

When we approach management as we approach experiments, and consider the information value of alternative candidate actions in evaluating choices, management becomes *actively adaptive*. There is a risk, however, because experimental management involves manipulating not just a small plot in an agricultural field, or in a culture pond, but manipulating the environment as a whole. The costs can be great, at least in the short term, especially when experiments involve actions that are radically different from those that would be optimal if learning were ignored. Experiments are worthwhile only as long as the expected benefits derived from learning overcompensate the short-term costs of implementing them.

Experiments are not free, but neither is ignorance: some short-term sacrifices may be worthwhile if they can lead to better management in the future.

Whether the strategy is actively or passively adaptive, a key to adaptive management is that system responses are monitored, effects of past actions are evaluated, and management is able to respond in an effective and timely manner to what is learned.

CONSEQUENCES OF NONADAPTIVE MANAGEMENT

The thrust of actively adaptive management is that we cannot hope to understand the complex system we are trying to manage unless we experiment with it. What then are the consequences of not taking an actively experimental approach to natural resource management?

For example, consider the problem of designing a reserve system for an endangered wildlife species that depends on old-growth forest in a landscape that is being commercially logged. Given that only a certain total area can be set aside for conservation, the problem of reserve design is to decide how to distribute these reserves across the landscape. Large reserves are more likely to enable populations to persist but if a catastrophe occurs the entire population could be destroyed. Small reserves can spread the risk of a catastrophic decline but are more likely to suffer from problems of small population size. Which tactic is more effective has been the subject of strong debate for many years. Using *Population Viability Analysis* (PVA)—a computer simulation method for assessing the viability of populations—conservation biologists have resolved the reserve-size debate for some specific species. For example, Lindenmayer and Possingham[14] showed that, given a fixed area that can be set aside, the reserve size that minimizes extinction probability of Leadbeater's possum (*Gymnobelidus leadbeateri;* Fig. 4) is about 100 ha. This example could equally apply to reserve design for the spotted owl (*Strix occidentalis caurina*).[15] Imagine that we followed the "optimal" rule and created a large number of reserves of fixed size. Now imagine an ecologist 100 years hence, asked to asses the performance of the reserves in preserving the species. Because each reserve is the same size, our future ecologist is only able to see how that particular design worked, but cannot evaluate whether alternative designs could have done better. The key to learning is to try and compare the effects of contrasting management actions.

The prediction of an optimal reserve size is only a best guess. Using different parameters, the optimal size for Leadbeater's possum can range from 25 to more than 100 ha.[14] What if we are

Figure 4. Leadbeater's possum is a small, rare marsupial now confined within the tall eucalyptus forests of Central Victoria, Australia. The loss of old-grown forest due to catastrophic wildfires and logging has threatened this species with extinction. Permanent reservation of key forest patches appears to be the best strategy for conservation. But what would be the most effective reserve design given that there are constraints in the amount of area that can be set aside? (Photo by D. Lindenmayer)

wrong? The nonadaptive approach may have long-term and potentially disastrous consequences. By contrasts, using adaptive management we would require that reserves vary in a fashion conducive to learning, establishing reserves of different sizes replicated along the landscape.

Although this represents an experimental approach to reserve design, is it adaptive? One might argue that once reserves are established there is little room for adaptive management. It is true that changing the size of old-growth reserves is likely to be difficult; however, it is not impossible. Exactly how we might go about it must be considered in the experimental design phase. For example, we might return to the forest at regular intervals for 50 years to determine whether populations in the different-sized reserves were increasing or decreasing. At the least, reserves of different sizes could be sampled for the presence of the threatened species. Suppose all the small reserves still contain populations, and the density of animals in small reserves is higher than their density in large reserves. Having learned that, we would start creating more small old-growth reserves. Alternatively, we might find that the best size appears to be the biggest reserve we initially established. Again, if we have an adaptive program, we would consolidate suites of small reserves or expand the size of medium-sized reserves. This may be a slow process, but remember that the consequences of a fixed reserve size is that we cannot tell which size of reserve works most effective—let alone refine our strategy to adequately protect the species for minimum cost.

Adaptive management experiments need to be carefully thought through to improve the chances of achievement management goals. Some uncertainties may be irrelevant and others may have large economic and/or conservation consequences.

For example, wildlife in Western Australia has been devastated by introduced predators this century. Many species of native mammals are severely threatened by the European red fox. A long-term experimental fox-control program has led to partial recovery of several species.[16] Close to 700,000 ha of forest has been baited using extracts from a native plant that are lethal only to introduced animals. Monitoring of fauna populations is undertaken in areas subjected to four experimental treatments: a no-baits control, and areas that are baited twice, four times, and six times per year. A nonadaptive approach would instead impose a fixed level of pest control over the entire region and no information would be provided about which level of control is most effective. Since time and money are limited, predator numbers will never be reduced to zero; there must be a trade-off between a low level of predation control everywhere and a high level of predation control in a few spots. It is possible, for example, that a very effective fox control leads to an increase in a competitor, such as a rabbit, that also disadvantages the threatened species. Without experimental management little or no information will be gained, which ultimately reduces the effectiveness of management.

The key to learning is to try and compare the effects of contrasting management actions.

In many cases, opportunities to learn are lost through failure to monitor. When major fishing grounds are closed, or reserves are set aside, or when natural enemies are released to control a pest, monitoring protocols should be adjusted to closely follow the effect of those measures. Fisheries crises have prompted the implementation of a suite of measures to drastically curtail fishing pressure at great expense to the fishing communities that depend on those fisheries. Unfortunately, resources are generally not adequate to close monitor the effect of those drastic measures, or to assess how effective different tactics may be at achieving the objective of lowering fishing mortality.

POTENTIAL FOR ADAPTIVE MANAGEMENT IN PEST CONTROL

The lack of adaptive management in pest control in agriculture and forestry requires special mention. It is ironic that adaptive management is best developed in ecosystems—marine fisheries—where it is hardest to get the necessary information about the system's behavior and response to control actions, and least developed where these tasks are most readily accomplished, *i.e.*, in pest control. The time is clearly ripe for a strong and organized application of adaptive management to pest control.

Adaptive management could usefully be applied at several levels in pest control, and we mention just three. The first is a direct extension of fisheries' practices on a shorter time scale, namely week to week decision-making in the application of control measures such as pesticide spraying, or environmental manipulation (*e.g.*, level of irrigation) that can affect pest numbers, in response to the status of the crop, the pest, and perhaps its natural enemies. Information on the status of these variables is relatively easily and accurately obtained by monitoring. There is almost always spatial replication in crops so different strategies can be applied simultaneously in different places and the system's response rapidly monitored. Most important, there is a wealth of information about crops and pests and their enemies.[17,18] "Expert models" have been developed for a few pest problems, though their implementation has hardly begun (Mills and Mumford, personal communication).[19] These are programs, based on a model of pest and/or crop dynamics, that take as input the current state of the real system and give advice to the farmer on appropriate actions.[20] However, they are neither passively nor actively adaptive since there is no framework for modifying the underlying "expert model" in light of monitoring results following various control actions.

The two other applications are in classical biological control, which involves the release of natural enemies to control pests—usually herbivorous insects in the case of weeds, and predatory or parasitic insects in the case of insect pests. A key question is: If we have reared in the laboratory a group of the enemy that we wish to release, and have many potential sites that could benefit from the enemy, what is the optimal set of releases to achieve the greatest overall level of control? Many practitioners would split the lot evenly and release the same number at all sites. A failure is complete. Not only do no agents establish, but no real information (other than that too few were released!) is gained. If, instead, there is establishment, who is to say that fewer agents might not have fared just as well? Given the costs of rearing agents, not to investigate what the optimal size is is a terrible waste of resources. A mixed-release strategy provides an opportunity for learning about the probabilities of establishment of different sizes.[21]

Finally, adaptive management could be used over a much longer time scale to develop a framework for guiding the choice of natural enemy species that should be released to control different types of pests. Practitioners do make use of past experiences, of course. For example, they tend to look for new natural enemies that belong to the same genus as a previously successful enemy.[22] But there is again no formal framework for incorporating new information or for modifying guiding models; monitoring different control strategies is inadequate (usually because there is little funding for such "research"), and natural enemies are rarely released in an experimental way as suggested by actively adaptive management.

Yet biological control presents a good opportunity for actively adaptive management. On the one hand, biological control at present is mainly a purely trial and error process, with rather little learned from each trial, and even less that has been learned has been formalized. Hundreds of enemy species have been released at thousands of sites and in very few cases has there been monitoring of the results to explain why some of these "experiments" failed and others succeeded. For example, 52 species of natural enemies were released to control California red scale, a major pest of citrus, the last of which was the highly successful parasitoid, *Aphytis melinus*. We do not know why the first 51 were failures, or what distinguishing feature made *A. melinus* successful.[23] On the other hand, a substantial body of theory has been developed, much of it based on experiments and information about individual properties, which attempts to explain some results retrospectively or to provide some guiding principles.

The overall process of biological control could clearly benefit from an organized attempt to develop competing models for the selection and use of natural enemies, to monitor the consequences of such releases, and to adapt the guiding framework in the light of results. Again, the spatially replicated nature of agriculture and forestry is well adapted to actively adaptive management. For example, a major issue in biological control is whether it is better to release several enemy species or only a single "optimal" one. Since agents typically are released in sequence as they become available, we have no controlled information on this question. However, to the extent that it is precautionary to do so, a well-designed program could release a range of combinations of enemies in replicated situations to test the underlying competing models.

EXPERIMENTAL MANAGEMENT IS NO PANACEA

Experimental management, of course, has limitations, some of which may explain why actively adaptive management has not been more commonly implemented. The major ones are constraints in the policies that can be considered, difficulties in monitoring populations and their responses to interventions, lags in system responses, and limits in our ability to depict all possible states of nature.

Some Policies May Not Be an Option

At the core of actively adaptive management is the opportunity to choose among alternative actions, some of which are more informative than others. Choices are restricted, however, by social concerns or biological constraints. As a result, not only the potential for experimentation is restricted, but the opportunities to respond to what is known or learned are also restricted. Experiments too easily become an academic exercise for classrooms and laboratories, as opposed to a practical and powerful tool for learning in the real world.

A typical case of restricted options is that of irreversible decisions, in which we cannot undo the consequences of a management action. For example, once an exotic species is introduced (as in biological control), it is usually difficult to eradicate. Other kinds of actions, such as the construction of big engineering projects or the development of agriculture, can in theory be undone, but in practice they are irreversible due to socioeconomical and political constraints. Even if they were discontinued, their effects may be long term or essentially irreversible. This is also true for interventions that are initially considered remedial actions, but once established are there to stay even after the initial objective is achieved. The case of hatcheries constructed to help rebuild depleted fish stocks is a good example.[24]

Learning is also restricted when it requires the implementation of actions with unacceptably high risks. For most conservation problems, e.g., a big concern is the dynamics of populations at low numbers when there is a possibility that per capita rates for birth or recruitment may be very low. Although the only way to learn about population dynamics at low numbers is to drive the population to low numbers, the very nature of the conservation problem makes this "experiment" impracticable. The benefits of learning about these mechanisms may be completely outweighed by the perceived risks of the actions.

Monitoring May Be Inadequate

Our ability to assess how the system responds to management actions can be limited by several factors. In many settings, variables of interest can only be measured very imprecisely. For example, the abundance of rare or elusive populations that are difficult to sample is hard to estimate with any accuracy. Fisheries stock assessment methods have been notorious for their failures, especially when there are no surveys of abundance conducted independently of the fishery. Inadequate monitoring affects management performance in two ways. First, the results of a perfectly designed experiment can be blurred by the lack of precision of the assessment. Second, assessment errors can jeopardize our ability to implement particular management options. Suppose, for example, that we want to limit the harvest of a fish stock to a certain faction considered to be safe. How can we determine a catch quota based on this policy if we only have a very crude estimate of how many fish are in the water? Without better stock assessments even the correct management model may fail.

Responses to Management Actions May Take Too Long

The responses of natural systems to some interventions, such as community responses to manipulations of habitat or species composition, typically take place over a very long time. If the feedback between responses and actions takes inordinately long, the practical value of adaptive management decreases.

We May Fail to Depict All Possible States of Nature

Although a distinctive aspect of adaptive management is that the uncertainty about the dynamics of populations is explicitly considered, in many cases we are unable to specify all the potential ways in which nature may respond in the future. Models, by definition, simplify complex processes and may miss important characteristics of the system under study. A model can be wrong in two ways. First, it may fail to include relevant features of the dynamics. Single species models, e.g., exclude predators or competitors, which could be important in determining the fate of the population. Closed population, nonspatial models ignore the exchange of individuals with other populations and how that exchange is affected by the spatial arrangement of habitat and other populations. Second, the "rules" that govern the dynamics of a natural system may, with time, change altogether: natural selection may lead a pest population to become resistant to a pesticide; progressive habitat degradation may pose an increasing threat to species conservation; and oceanographic conditions may change over time scales of decades, strongly altering the structure and dynamics of marine ecosystems and the productivity of harvested populations. It may not be wise to conduct deliberate management experiments at great costs if what we can learn from them may not be of much use in the future.

A good example of the possible futility of implementing experimental policies involves the challenge created by changing oceanic conditions. Evidence is accumulating from retrospective studies linking prolonged periods of increased or decreased productivity of different fish stocks to climate changes.[25,26] The shift in climatic regime that apparently took place in the North East Pacific Ocean around 1976[26] is one such case. A marked increase in recruitment of Pacific halibut coincided with that regime shift. In the late 1980s, before the effects of that shift were apparent in the fishery statistics, alternative hypotheses about factors driving a quasicyclic trend in recruitment were considered for their management implications.[27] Experimental policies were evaluated as a way to try to separate the potential effects of environmental changes from those of changes in the size of the reproductive stock.[28] Ten years down the road, the picture that emerged contradicts all the scenarios considered plausible when experimental policies were evaluated. The apparent cycle in recruitment broke down, and new data do not support the idea that high stock sizes negatively impact recruitment, such as was apparent before. The experimental policies designed for the old hypotheses would have failed had they been implemented. Climate change in general is a problem for "model identification" in all areas of population management.

ADAPTIVE MANAGEMENT AND THE PRECAUTIONARY APPROACH

The precautionary approach[29] states that we should not proceed with ecological intervention unless we are reasonably sure that this will not cause a significant long-term loss of productivity or a significant long-term impact on the environment. The precautionary approach has been adopted by several countries and agencies as a prudent way to pursue ecologically sustainable development.

At first sight adaptive management might appear to be at odds with the precautionary approach. A program of adaptive management encourages us to exploit the system to gain information, while the precautionary approach appears to imply that we must gain the information first, and then exploit the system. In fact, the two approaches are complementary; indeed we believe that the precautionary approach forces us into being adaptive managers.

> **The precautionary approach forces us into being adaptive managers.**

Because it is impossible to predict a priori the consequences of many large-scale or long-term actions, most of the best information comes when we experiment with differing actions. Combining the precautionary approach and adaptive management means:

- Using information from other species and our general knowledge about population dynamics to build a range of conceptual models about how the system works;
- Experimenting with alternative management regimes while ensuring that, given the worst case scenario, any action we are taking has an acceptably low risk of long-term significant damage;
- Monitoring the consequences of the actions;
- Discarding models, and refining the best models, as new information becomes available and we move toward a robust management strategy.

In summary, the precautionary approach requires that experimental management must, in the first instances, be conservative.

For example, in fisheries one means of taking a conservative approach is to declare a substantial part of the range of a species a reserve. Indeed, Clark[30] advocated that an effective hedge against overexploitation is to close 50% or more of the habitat of a commercial species to fishing. How well the reserve functions depends in part on how effective it is in reducing fishing pressure on the resources, something that needs to be evaluated by closely monitoring the responses of fish and fisheries.

Unfortunately, conservation groups often resist adaptive management, because they confuse conservation and preservation or do not understand the importance of learning as we manage human intervention of ecosystems. A case study that exemplifies this difficulty is the management of recreational fisheries in the Great Barrier Reef. An adaptive management program was designed for line and spear fishing by Mapstone et al.[31] The plan involved a complex experimental design with different reefs subject to different levels of fishing: a closed control treatment (reefs that had been closed to fishing to remain closed), and an initial fishery treatment (reefs that had been closed to be opened to "at will" fishing for a year). The treatment that involved opening reserved reefs to "at will" fishing angered some sections of the conservation movement. Indeed, there has been intensive, political lobbying at federal and state levels to stop this adaptive management plan.

ADAPTIVE MANAGEMENT IS IMPERATIVE

There is no silver bullet that will protect our fish, forests, food, and biodiversity.[32] Nonetheless, adaptive management must be adopted and practiced. The reason is simple: adaptive management is the best mind-set for ecological intervention. We cannot control or manage populations or ecosystems; rather we control the level of human interaction with and intervention in natural systems. Adaptive management forces us to acknowledge uncertainty and our ignorance about natural systems; it is a hubris-reducing mechanism. Adaptive management also forces us to evaluate the effects of past actions as part of the management plan,[32] and implies that management is able to respond effectively in consequence. Finally, adaptive management is based on the recognition that our actions in the future will change as new information is obtained; it forces us to be flexible and to expect the unexpected. Biology has advanced so rapidly as it has because experiments are used to learn about how organisms work.[33] Resource managers should increasingly appreciate that interventions are experiments, and better meld experimentation and management.

> **Adaptive management is a mind-set for ecological intervention—it forces us to expect the unexpected.**

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