Adaptive Management of National Park Ecosystems

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MANAGEMENT OF NATIONAL PARK ECOSYSTEMS (i.e., national parks and the larger ecosystems in which they are located) is challenging for two reasons. First, national parks face numerous internal and external threats that are increasing over time (Dilsaver 1994; Prato 2005). National Park Service (NPS) policy encourages park managers to use their statutory authorities to protect natural resources and park values from these threats. In this regard, NPS policy states: "Strategies and actions beyond park boundaries have become increasingly necessary as the National Park Service strives to fulfill its mandate.... Recognizing that parks are integral parts of larger regional environments, the Service will work cooperatively with others to ... protect park resources and values and ... address mutual interests ... such as compatible economic development and resource and environmental protection" (NPS 2001). Canada's first State of the National Parks Report recognized that "none of the parks was immune to internal and external threats" and cited "water pollution, poaching, and logging on lands adjacent to park boundaries as some of the major threats to the integrity of parklands" (McNamee 2002).

Second, managing national park ecosystems is challenging because park managers cannot accurately determine ecosystem states and predict the outcomes of management actions due to uncertainty. Four sources of uncertainty arise. First, variability in social, demographic, ecological, and economic factors makes it difficult to infer the state of an ecosystem from observed conditions and predict ecosystem responses to management actions in advance of their implementation. Second, sampling and measurement errors make it difficult to precisely measure ecosystem conditions. Third, incomplete knowledge of ecosystems prevents accurate assessment of ecosystem states. Fourth, there is often disagreement or uncertainty about the attributes of desirable ecosystem states (Peterman and Peters 1998; Conroy 2000).

Adaptive management (AM) provides an appropriate framework for managing ecosystems subject to multiple sources of uncertainty (Prato 2000, 2003, 2005). Specifically, AM: (1) increases the rate at which policy makers and resource managers acquire knowledge about ecological relationships; (2) aids management decisions through the use of iterative hypothesis-testing; (3) enhances information flows among policy makers; and (4) creates shared understandings among scientists, policy-makers, and managers (Peterman 1977; Holling 1978; Clark et al. 1979; McLain and Lee 1996; Wondolleck and Yaffe 2000).

This article proposes an AM framework for national park ecosystems. The next section presents an overview of AM. The third section discusses the use of AM for national park ecosystems. The fourth section describes the impacts of land development on ecosystems. The fifth section contains a hypothetical example of AM of Montana's Northern Continental Divide Ecosystem for recovery of grizzly bears. A summary and conclusions are given in the last section.

Overview of adaptive management

The concept of AM surfaced in the mid-1970s as a way of managing ecosystems under uncertainty (Holling 1978; Walters and Holling 1990; Irwin and Wigley 1993; Walters 1996; Parma et al. 1998). The basic premise of AM is that "if human understanding of nature is imperfect, then human interactions with nature [e.g., management actions] should be experimental" (Lee 1993). Kohm and Franklin (1997) state that "adaptive management is the only logical approach under the circumstances of uncertainty and the continued accumulation of knowledge." Woodley (2002) points out that, "because of the difficulty in predicting ecosystem response, active management should be undertaken in national parks using adaptive management techniques."

AM is useful in making decisions about the state of an ecosystem and ecosystem responses to alternative management actions when there is uncertainty. It involves major investments in research, monitoring, and modeling to test alternative hypotheses about sustainable use and management of natural resources (Smith and Walters 1981; Hilborn et al. 1995; Walters and Green 1997). In an AM approach, public land managers experimentally test management actions so as to maximize their capacity to learn about ecosystem responses to those actions while simultaneously attempting to satisfy management objectives.

AM can be passive or active. Passive AM uses models to predict ecosystem responses to management actions and select best management actions, and employs monitoring data to revise the parameters of the models (Walters and Hilborn 1978; Hilborn 1992). Passive AM is relatively simple and inexpensive to apply because it does not require replication and randomization of treatments. Unfortunately, this feature makes passive AM knowledge about ecosystem states and responses to management actions unreliable (Wilhere 2002).

Active AM tests hypotheses about ecosystem states and responses to management actions by treating management actions as experiments that generate information for testing hypotheses about ecosystem states and responses. For example, a manager could use AM to test hypotheses about whether a national park ecosystem is in a desirable or undesirable state. If the state is judged to be undesirable, then management actions should be taken to achieve a desirable state. Unlike a trial-and-error approach that provides slow and random accumulation of information, the information provided by active AM is reliable (Lee 1993).

There are ten prerequisites for successful application of active AM (Lee 1993; Wilhere 2002; Prato and Fagre 2005).

1. *There must be a mandate to take action in the face of uncertainty*. National park managers need to realize that the outcomes of most management actions are uncertain. Experimentation and learning in national park ecosystems are at best secondary objectives that are likely to be dismissed or not even proposed if they conflict with primary objectives, such as recreation and natural resource protection. However, most

national park managers know that ecosystem states and effects of certain management actions are uncertain.

2. *Preservation of pristine environments is no longer an option*. While many national parks have remarkable natural and cultural resources, very few are totally pristine. Even national parks that are relatively pristine are subject to human disturbance both within and outside their boundaries and, hence, must be treated as managed ecosystems.

3. *Human intervention is not capable of producing desired outcomes predictably*. AM is not needed when ecosystem states and management outcomes are predictable. Unpredictability occurs because management actions have uncertain outcomes.

4. *There must be sufficient institutional stability to measure long-term outcomes*. AM experiments need to be carried out over the long term in order to capture the relatively slow responses of ecosystems to human interventions. The institutional environment for many national parks is stable because the management agency is charged with managing the park in accordance with objectives established in an organic act. However, there are sources of institutional instability, including turnover in upper management, declining budgets, and, in some countries, political instability and war. In any event, institutional stability is typically outside the control of experimenters and managers.

5. *It must be possible to formulate hypotheses*. Based on past experience and scientific knowledge, national park managers should be able to design experiments to test hypotheses about ecosystem states and responses to management actions. It is generally not technically, financially, or politically feasible to test all relevant hypotheses.

6. *Theory, models, and field methods must be available to estimate and infer ecosystem-scale behavior*. While scientific knowledge about ecological and socioeconomic relationships for national park ecosystems is incomplete, there is usually sufficient understanding of the ecosystem to design monitoring, research, and evaluation programs, and to design sampling schemes to collect the data needed to test hypotheses regarding ecosystem states and responses to management actions. AM increases knowledge by promoting learning. Preliminary results might indicate that the experimental design was faulty or certain management actions are not likely to achieve desirable ecosystem states or outcomes. The latter increases the pressure to change management actions before experiments are completed, which is disruptive.

7. *Decision-makers need to view management actions as experiments and uncertainty about outcomes as potential hazards*. The idea of experimenting with national park ecosystems, particularly highly visible ones, is not likely to be well received because it admits the possibility that management actions can fail to achieve desired social, economic, and ecological objectives. Park managers need to communicate these risks to the public and stakeholders and explain that even if experiments do not achieve desirable outcomes, they are valuable because they improve ecosystem knowledge.

AM for highly sensitive issues, like recovery of declining species, can be designed to minimize the risk of management actions failing to recover the species. For example, risky experiments can be done in an area of a national park ecosystem where human and environmental factors are easier to control. Minimizing the risk of adverse consequences needs to be balanced with maximizing the information value of experiments. Politicians seeking opportunities to increase their chances of re-election are likely to oppose experiments that could adversely affect the welfare of their constituents.

8. *Organizational culture must encourage learning from experience and the culture must value reliable information*. While national park managers are generally willing to learn from experience, they often evaluate their actions based on casual observation and unreplicated actions. Active AM requires setting in place monitoring, research, and evaluation programs that provide statistically reliable data for testing hypotheses about ecosystem states and the effectiveness of management actions in achieving desirable outcomes. If long-term learning through AM provides benefits to staff (usually the ones implementing the experiments) but not to managers, then a struggle is likely to ensue for organizational control.

9. *Resources must be sufficient to measure ecosystem-scale behavior*. Monitoring for AM is a long-term, expensive proposition, which makes AM vulnerable to insufficient budgets, changes in policy, and controversy. New managers and administrators may not understand or support an experimental approach to management.

10. *Decision-makers must care about improving outcomes over biological time scales.* The cost of monitoring controls and replication is high at the outset relative to the costs of unmonitored trial and error. National park managers may not have the motivation, patience, and budget to implement long-term AM experiments, especially if their term of office is significantly less than biological time scales, which is almost always the case. For example, a national park manager under pressure to sustain and increase visitation is likely to be less concerned with biological impacts of higher visitation, especially when the experiments needed to test hypotheses regarding those impacts require many years to complete.

Of the ten prerequisites for active AM, numbers 1, 2, 3, 5, 6, and 7 are likely to be satisfied, while numbers 4, 8, 9, and 10 are unlikely to be satisfied.

There are two ways to improve the success of AM. First, management actions need to be substantial in order to ensure that the natural variability inherent in ecosystems does not overwhelm the effects of management actions. Second, a management action needs to be relatively simple in order to ensure detection of ecosystem responses to that action. Due to ecological uncertainties, managers should expect to be surprised by certain management outcomes. Surprise should not be viewed as the failure to predict ecological responses, but rather an opportunity to learn more about the ecosystem (Lee 1993).

Even if conditions for implementing active AM are ideal, it has several limitations. First, it is more time-consuming, complex, and costly than other forms of management, such as passive AM, trial-and-error, and deferred action (Walters and Hilborn 1978; Walters and Holling 1990). Second, it can give faulty results when relevant variables are either ignored or not held constant (Smith 1997). Third, it has certain application pitfalls. For example, there have been instances of AM in New Brunswick and British Columbia, Canada, as well as in the Columbia River Basin, that relied extensively on the use of linear systems models, discounted non-scientific forms of knowledge, and paid inadequate attention to policy processes that promote the development of shared understandings among diverse stakeholders (McLain and Lee 1996). Fourth, AM forthrightly tests management actions that may not necessarily achieve desired outcomes, which can be politically unpopular (Lee 1993). These limitations can be alleviated by incorporating knowledge from multiple sources, using several systems models, utilizing new forms of cooperative decision-making (McLain and Lee 1996), and educating politicians and managers about the benefits and risks of AM.

Use of adaptive management

AM has been used or recommended for use in managing national parks. Banff National Park in Alberta, Canada, is using passive AM to develop its human use management strategy for the park. The strategy is expected to generate new knowledge and understanding (learning) about "the complex relationship between ecological integrity and human use" (Parks Canada 2001). Elk Island National Park in Alberta, Canada, is using an adaptive landscape management approach to manage populations of elk and bison in the park (Woodley 2002). The National Research Council (NRC) report on natural regulation of ungulates in Yellowstone National Park's northern range recommended that "to the degree possible, all management at YNP should be done as adaptive management" (National Research Council 2002a). The NRC report stated that active AM would improve scientific understanding of the consequences of different management actions and the park could continue natural regulation of ungulates within an AM framework.

The draft supplemental environmental impact statement (SEIS) for winter use in Yellowstone National Park, Grand Teton National Park, and the John D. Rockefeller, Jr., Memorial Parkway that connects the two parks proposed three management alternatives. Alternatives 2 and 3, which do not ban snowmobile use in these areas, employ AM to "mitigate impacts on visitor experience and access, wildlife, air quality and natural sound while allowing snowmobile access on all existing oversnow routes" (National Park Service 2002). The draft SEIS states that "the first step in adaptive management is to develop and implement a management scenario based on the best available information." This implies a passive AM approach. Specifically, Alternative 2 establishes interim visitor use limits for each of the six road segments having snowmobile use. Interim use limits are predicted to keep impacts of snowmobile use within acceptable limits defined in terms of standards for visitor experiences and park resources. Monitoring is done to determine whether use impacts violate the standards. If the latter occurs, then park managers decrease use limits and adjust related management actions in an effort to achieve the standards.

The Comprehensive Everglades Restoration Plan (CERP) is the world's "largest and most ambitious ecosystem restoration" project involving an expected expenditure of $8 billion over 30 years to restore the hydrology of South Florida, which includes Everglades National Park (Best 2000; Kiker et al. 2001; Sklar et al. 2001). A desirable feature of the CERP process is that planners have flexibility to refine and revise it "as part of [an] adaptive assessment process" (U.S. Army Corps of Engineers and South Florida Water Management District 2000). An adaptive learning approach is being used because ecosystem restoration at the scale and complexity of South Florida and the Everglades is beyond the current knowledge and experience base of the scientific community. Adaptive learning, which is the learning component of adaptive management, entails "continuous growth in understanding by scientists, managers, policy makers, political representatives and the public" (Kiker et al. 2001). Specifically, the shared understandings of ecological and socioeconomic processes that emerge from adaptive learning feed into the adaptive management process, particularly the formulation of management action(s).

Active AM is being used in the lower Colorado River, which flows through Grand Canyon National Park, to improve understanding of how water releases from Glen Canyon Dam influence sediment, fish, vegetation, wildlife and habitat, endangered and other special-status species, cultural resources, air quality, recreation, hydropower, and non-use values (Glen Canyon Adaptive Management Program 2003).

Impacts of land development

A major threat to the ecological integrity of national park ecosystems is the conversion of agricultural, ranch, and forest lands to residential, commercial, and resort developments. Land development reduces open spaces and increases road density, human use of roads, and landscape fragmentation, which are especially detrimental to large carnivores, such as grizzly bear, mountain lion, and wolves. For instance, studies show that the effectiveness of grizzly bear habitat decreases with increases in road density and human presence (Mace et al. 1996). Mortality risk is higher for grizzly bears that travel through fragmented landscapes because it increases their encounters with humans and vehicles (Harris and Gallagher 1989). Hence, one way to improve grizzly bear habitat is to restrict land development.

Restrictions on land development can take many forms, including decreasing housing density, requiring bear proof garbage containers, limiting the use of bird feeders, limiting the planting of fruit trees, and controlling other bear attractants. Such restrictions can be implemented by amending zoning and subdivision regulations and land use plans. In addition, it may be possible to improve grizzly bear habitat via land donations, land purchases, land trusts, land exchanges, and conservation easements (Brown 1999).

A hypothetical example

This section describes a hypothetical example of active AM for assessing grizzly bear recovery in the Northern Continental Divide Ecosystem (NCDE) in northwest Montana (see Figure 1). Grizzly bear is a threatened species in the NCDE. The NCDE covers 32,300 km^2 (8 million acres), and contains Glacier National Park, the adjacent Waterton/Castle area in southern Alberta, the Bob Marshall Wilderness complex, and private lands. It is one of six recovery zones defined in the Grizzly Bear Recovery Plan for the United States. The NCDE recovery zone contains the greatest number of grizzly bears (400+) and is the only zone contiguous to a strong Canadian population of grizzly bear. For these reasons, the NCDE may offer the best prospect for long-term survival of the grizzly bear (U.S. Fish and Wildlife Service 2003; U.S. Geological Survey, 2004).

The hypothetical example divides the NCDE into bear management units for the purpose of testing hypotheses about grizzly bear mortality and recovery. If hypothesis

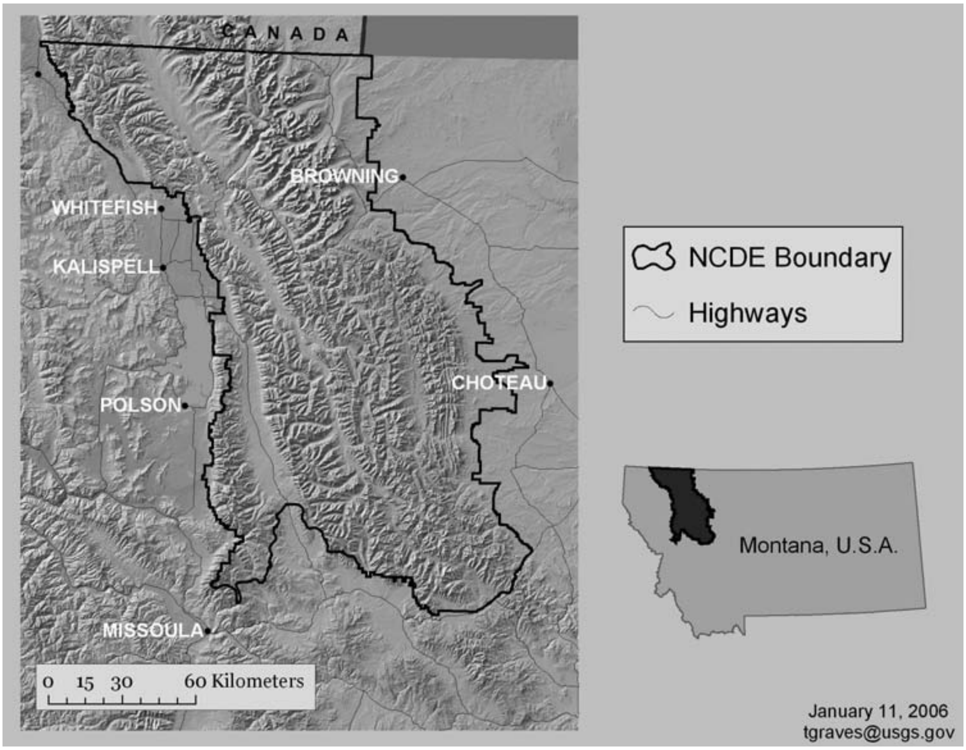

Figure 1. Grizzly bear distribution and recovery area in Northern Continental Divide Ecosystem. Source: U.S. Geological Survey (2004).

testing indicates that recovery is not being achieved in the ecosystem, then management action is taken to reduce mortality. To make the example concrete, the management action for improving grizzly bear habitat is to impose restrictions on land development in critical habitat areas. Land development in the ecosystem has an important bearing on grizzly bear recovery because the majority of human–bear conflicts and bear deaths occur on private land, which makes up 17% of the ecosystem (U.S. Fish and Wildlife Service 2005). Other management actions could be considered as well.

It is difficult to conduct true statistical experiments at the ecosystem scale. However, it is feasible to conduct pseudo-experiments to test hypotheses regarding grizzly bear recovery. Pseudo-experiments are not true statistical experiments because: (1) it is usually not feasible to have a control (e.g., another ecosystem in which the management action is not implemented); (2) it is often not possible to experimentally vary treatment levels (e.g., varying the rates of housing densities); (3) even if different treatments could be implemented in the same ecosystem, they may not be spatially independent (i.e., restricting housing densities in one bear management unit is likely to influence bear mortality in other units); and (4) it is difficult to control for other factors influencing bear mortality, such as weather, food availability, and logging operations.

The hypothetical example has two ecosystem states, Θ_C and Θ_I, two competing hypotheses, H_C and H_I, and two management actions, a_1 and a_2. Θ_C signifies the ecosystem state is compatible (C) and Θ_I signifies it is incompatible (I) with recovery of grizzly bear. H_C states the bear mortality rate is compatible ($\Theta = \Theta_C$) and H_I states the mortality rate is incompatible ($\Theta = \Theta_I$) with grizzly bear recovery goals for the NCDE. Management action a_1 imposes restrictions on land development and management action a_2 does not restrict land development on private lands. Prior probabilities for the two ecosystem states are $p(\Theta_C)$ and $p(\Theta_I)$, where $p(\Theta_I) = 1 - p(\Theta_C)$, and can be either estimated using suitable data or subjectively determined using expert knowledge, such as by the Delphi method. The latter is a structured procedure that uses questionnaires and controlled opinion feedback to collect and synthesize knowledge about a particular value from a group of experts (Bakus et al. 1982; Turoff and Linstone 2002). A subjective probability reflects the decision-maker's personal knowledge and beliefs about the likelihood of the hypotheses being true before experiments are conducted.

Posterior probabilities for Θ_C and Θ_I are calculated using Bayes' theorem as follows:

$$p(\Theta_C|X = X_0) = [p(\Theta_C)\ p(X = X_0|\Theta_C)]/p(X = X_0)$$

$$p(\Theta_I|X = X_0) = [p(\Theta_I)\ p(X = X_0|\Theta_I)]/p(X=X_0).$$

X is the number of sampled areas in the NCDE that have high rates of bear mortality, X_0 is a particular value of X, $p(X = X_0) = p(\Theta_C)\ p(X = X_0|\Theta_C) + p(\Theta_I)\ p(X = X_0|\Theta_I)$, and $p(X = X_0|\Theta_C)$ and $p(X = X_0|\Theta_I)$ are the likelihoods that $X = X_0$ given the ecosystem state is Θ_C and Θ_I, respectively. Likelihood functions can be estimated. For example, suppose X is normally distributed. The likelihood function for a sample drawn from this distribution has a normal distribution with sample mean z´ and standard deviation $s/(n)^{1/2}$, where s is the sample standard deviation and n is the sample size (Prato 2000).

Suppose 12 bear management units in the NCDE are randomly sampled (n = 12) and the number of units out of 12 with high bear mortality (X) determined. If test results do not lead to rejection of H_I, then mortality rates are high and land development restrictions are justified. Otherwise, land management restrictions are not justified. In an actual application, the sample size would be greater than 12 provided there are more than 12 bear management units in the NCDE. The hypothetical example uses a sample size of 12 in order to keep the following example tables manageable. Table 1 summarizes hypothetical likelihoods or probabilities of values of X between 0 and 12, the posterior probability that the ecosystem state is Θ_I for $p(\Theta_I) = 0.84$, the most likely ecosystem state (Θ_C or Θ_I), and the resulting decision regarding whether or not to restrict land development in the NCDE.

Hypothetical sampling results indicate that land development should not be restricted (H_I rejected and a_2 selected) for $X \leq 4$ because the posterior probabilities for these values of X are less than 0.05, a commonly specified value of α (Type I error, or probability of deciding not to restrict land development when the ecosystem state is incompatible with recovery). Land development should be restricted for $9 \leq X \leq 12$ (H_I not rejected and a_1 selected) because the posterior probabilities for these values of X exceed 0.95. The latter is the probability of

Number of areas with high rates of bear mortality[a] (X)	Likelihood of observing X when $\Theta=\Theta_I$ $p(X\|\Theta=\Theta_I)$[b]	Likelihood of observing X when $\Theta=\Theta_C$ $p(X\|\Theta=\Theta_C)$[c]	Posterior probability of Θ_I $p(\Theta_I\|X)$[a]	Most likely ecosystem state	Land development decision
0	0.000	0.001	0.000	Θ_C	do no restrict (a_2)
1	0.000	0.008	0.000	Θ_C	do no restrict (a_2)
2	0.000	0.034	0.000	Θ_C	do no restrict (a_2)
3	0.000	0.092	0.000	Θ_C	do no restrict (a_2)
4	0.001	0.170	0.030	Θ_C	do no restrict (a_2)
5	0.003	0.222	0.066	inconclusive	ambiguous
6	0.016	0.212	0.284	inconclusive	ambiguous
7	0.053	0.149	0.651	inconclusive	ambiguous
8	0.133	0.076	0.902	inconclusive	ambiguous
9	0.236	0.028	0.978	Θ_I	restrict (a_1)
10	0.283	0.007	0.995	Θ_I	restrict (a_1)
11	0.206	0.001	0.999	Θ_I	restrict (a_1)
12	0.069	0.000	1.000	Θ_I	restrict (a_1)

a. Based on bear mortality in the area resulting from human-bear interactions (excluding deaths from natural causes) relative to recovery goals.

b. Θ_I indicates the ecosystem state is incompatible with grizzly bear recovery.

c. Θ_C indicates the ecosystem state is compatible with grizzly bear recovery.

Source: Adapted from Bergerud and Reed (1998).

Table 1. Hypothetical likelihoods that X areas out of 12 have high rates of grizzly bear mortality for ecosystem states Θ_I and Θ_C, posterior probabilities for Θ_I, and associated land development decision.

deciding to restrict land development when the ecosystem is incompatible with recovery (power of the test). For $5 \leq X \leq 8$, posterior probabilities are between the Type I error (0.05) and power of the test (0.95), which indicates inconclusive or ambiguous evidence about the most likely state of the NCDE with respect to grizzly bear recovery. The decision of whether or not to restrict land development is ambiguous for $5 \leq X \leq 8$.

Ambiguous decisions can be eliminated using a *Bayes action*. The latter minimizes the expected loss or equivalently maximizes the expected gain over all possible actions with respect to the posterior probability distribution. If a_j is selected when the ecosystem state is Θ_i, then expected loss is $L(a_j, \Theta_i)$, or equivalently expected gain is $G(a_j, \Theta_i) = -L(a_j, \Theta_i)$ where $i, j = 1, 2$. The Bayes action is determined by comparing the *Bayes gain* (BG) (Morgan and Henrion 1990) for the two management actions using the hypothetical expected gains shown in Table 2. (The BG is a weighted average of the gains for an action

Ecosystem state	Possible action	
	a_1[a]	a_2[b]
Compatible (Θ_C)	$G(a_1, \Theta_C)$ = -\$1,000/acre	$G(a_2, \Theta_C)$ = \$800/acre
Incompatible (Θ_I)	$G(a_1, \Theta_I)$ = \$500/acre	$G(a_2, \Theta_I)$ = -\$1,500/acre

a. Restrict land development.

b. Do not restrict land development.

Table 2. Hypothetical expected gains for a_1 and a_2 with ecosystem states Θ_C and Θ_I.

with weights given by the posterior probabilities for ecosystem states.) For X = 8 (i.e., one of the values of X for which the decision is ambiguous), BGs for a_1 and a_2 are:

$$BG(a_1) = p(\Theta_I|X = 8)\, G(a_1, \Theta_I) + p(\Theta_C|X = 8)\, G(a_1, \Theta_C) = \$353$$

$$BG(a_2) = p(\Theta_I|X = 8)\, G(a_2, \Theta_I) + p(\Theta_C|X = 8)\, G(a_2, \Theta_C) = -\$1,275$$

The Bayes action is a_1 if $BG(a_1) > BG(a_2)$, or a_2 if $BG(a_2) > BG(a_1)$. Therefore, a_1 (restricting land development) is the Bayes action for X = 8. BGs and Bayes actions for all possible values of X are given in Table 3. H_I is not rejected and the Bayes action is not to restrict land development (a_2) for $X \leq 6$. H_I is rejected and the Bayes action is to restrict land development (a_1) for $X \geq 7$.

Table 3 represents hypothetical results for one pseudo-experiment. Ideally, AM for grizzly bear recovery should be implemented as a sequence of pseudo-experiments. To illustrate the procedure, let X = 6 for the first experiment. If the hypothetical results for the first experiment are as shown in Table 3, then H_I is rejected for X = 6 and land development restrictions are not imposed. Suppose land development continues after the first experiment is completed prompting the decision-maker to conduct a second experiment—say, five years after the first one. The posterior probability from the first experiment, $p(\Theta_I|X=6) = 0.284$, becomes the prior probability of Θ_I for the second experiment. Since the benefits and costs of restricting land development are likely to change over time, expected gains (see Table 2) should be updated each time a new experiment is conducted. Suppose the second experiment favors nonrejection of H_I. This implies land development should be restricted. These hypothetical results indicate mortality rates for grizzly bear worsened in the five-year period between the first and second experiments. If financially feasible, the pseudo-experiments should continue at least until the species is recovered.

The NRC report on recovering the Missouri River Ecosystem recommends formation of a "representative stakeholder committee to develop a basinwide strategy, conduct assessments, review plans, and provide oversight of the implementation of

Number of areas with high rates of bear mortality (X)	Posterior probability of Θ_I $p(\Theta_I\|X)^a$	Bayes Gain for a_1 ($/acre)	Bayes Gain for a_2 ($/acre)	Bayes action for land development
0	0.000	-1,000	800	do not restrict (a_2)
1	0.000	-1,000	800	do not restrict (a_2)
2	0.000	-999	798	do not restrict (a_2)
3	0.000	-996	793	do not restrict (a_2)
4	0.030	-976	763	do not restrict (a_2)
5	0.066	-891	632	do not restrict (a_2)
6	0.284	-585	163	do not restrict (a_2)
7	0.651	-22	-700	restrict (a_1)
8	0.902	353	-1,275	restrict (a_1)
9	0.978	467	-1,449	restrict (a_1)
10	0.995	493	-1,489	restrict (a_1)
11	0.999	499	-1,498	restrict (a_1)
12	1.000	500	-1,500	restrict (a_1)

a. Same as the fourth column in Table 1.

Source: Adapted from Bergerud and Reed (1998) and Prato (2005).

Table 3. Hypothetical Bayes gains and Bayes posterior decisions for all possible values of X.

adaptive management initiatives" and collaborative involvement of a broad range of stakeholders in adaptive management of the Missouri River ecosystem (National Research Council 2002b). Similarly, Gunderson et al. (1995) recognize that "involvement and education of people who are part of the ecosystem as crucial to building resilient solutions and removing gridlock." Prato (2003) suggests forming an adaptive management working group for the Waterton–Glacier International Peace Park. Since grizzly bear recovery is of interest to a wide range of stakeholders, it would be worthwhile to form an AM working group to facilitate recovery of grizzly bear in the NCDE. The working group would evaluate experimental results and decisions about whether or not to restrict land development; compare the social, economic, and ecological consequences of restricting land development; and recommend specific ways to restrict land development when justified by the pseudo-experiments.

Summary and conclusions

Management of national park ecosystems is challenging because ecosystems face a multiplicity of threats and impacts, many of which are external to the park but internal to the greater ecosystem in which the park is located. In addition, management of national park ecosystems is subject to multiple sources of uncertainty. National park managers in North America have been encouraged to develop strategies and actions to protect natural resources and values from external threats.

AM has been used or recommended for use in managing national park ecosystems when there is uncertainty regarding the state of the ecosystem and ecosystem responses to management actions. The basic premise of AM is that management actions need to be experimental due to imperfect understanding of ecological processes. Although passive AM is relatively simple and inexpensive to apply, the lack of replication and randomization of treatments renders the knowledge it provides about ecosystem states and ecosystem responses to management actions unreliable. Active AM views management actions as treatments in statistically valid experiments that replicate and randomize treatments, and generate data suitable for testing hypotheses about the state of an ecosystem and ecosystem responses to management actions. Some prerequisites for active AM are unlikely to be satisfied.

Land development in the NCDE has accelerated habitat loss and degradation for grizzly bear, which is a threatened species in the NCDE. Active AM experiments are impractical for managing grizzly bear recovery. The hypothetical example presented here conducts pseudo-experiments that involve two ecosystem states, two competing hypotheses, and two management actions for bear recovery. Pseudo-experiments provide data on the number of sampled areas in the NCDE having unacceptable rates of bear mortality (X). Bayes' theorem is used to calculate posterior probabilities that combine the data with prior probabilities of ecosystem states, and likelihood functions for X given the ecosystem state is incompatible with recovery. Posterior probabilities are used to decide whether or not to restrict land development in the NCDE or implement another policy in order to recover grizzly bear. The hypothetical example leads to ambiguous decisions about ecosystem states and whether or not to impose restrictions on land development for certain values of X.

Ambiguous decisions can be eliminated by determining the Bayes action, which minimizes the expected loss or, equivalently, maximizes the expected gain over all possible actions with respect to the posterior probability distribution. The Bayes action is that which has the highest Bayes gain (BG). The latter is a weighted average of the gains for an action with weights given by the posterior probabilities for ecosystem states. Determination of the Bayes action requires information on the expected gains with different management actions. Implementing active AM with Bayesian statistics entails conducting sequential pseudo-experiments in which the posterior probability from one experiment becomes the prior probability for the subsequent experiment.

It is best to implement AM with the assistance of a working group that reviews experimental results; evaluates the social, economic, and ecological consequences of restricting land development; and recommends policies to restrict land development when justified by experimental results. National park managers, community planners, scientists, environmental groups, and developers are likely candidates for membership in an AM working group for grizzly bear recovery.

References

Bakus, G.J., W.G. Stillwell, S.M. Latter, and M.C. Wallerstein. 1982. Decision making: With application for environmental management. *Environmental Management* 6, 493–504.

Bergerud, W.A., and W.J. Reed. 1998. Bayesian statistical methods. In *Statistical Methods for Adaptive Management Studies.* Land Management Handbook no. 42. V. Sit and B. Taylor, eds. Victoria: Research Branch, British Columbia Ministry of Forestry, 89–104.

Best, G.R., ed. 2000. *Greater Everglades Ecosystem Restoration (GEER) Science Conference: Defining Success (Proceedings).* Miami: South Florida Ecosystem Restoration Task Force and Working Group and U.S. Geological Survey.

Brown, P. 1999. Tools for ecological stewardship. In *Ecological Stewardship: A Common Reference for Ecosystem Management.* Vol. III. W.T. Sexton, A.J. Malk, R.C. Szaro, and N.C. Johnson, eds. Oxford: Elsevier Science, 463–496.

Clark, W.C., D.D. Jones, and C.S. Holling. 1979. Lessons for ecological policy design: A case study of ecosystem management. *Ecological Modeling* 7, 1–53.

Conroy, M.J. 2000. Mapping biodiversity for conservation and land use decisions. In *Spatial Information for Land Use Management*. M.J. Hill and J. Aspinall, eds. Amsterdam: Gordon and Breach Science Publishers, 145–158.

Dilsaver, L.M., ed. 1994. *America's National Park System: The Critical Documents*. Lanham, Md.: Rowman & Littlefield.

Franklin, J.F. 1997. Ecosystem management: An overview. In *Ecosystem Management: Applications for Sustainable Forest and Wildlife Resources*. M.S. Boyce and A. Haney, eds. New Haven, Conn.: Yale University Press, 21–53.

Glen Canyon Adaptive Management Work Group. 2003. Glen Canyon Adaptive Management Program. On-line at www.uc.usbr.gov/amp/amwg/dsc_amwg.html.

Gunderson, L.H., C.S. Holling, and S.S. Light, eds. 1995. *Barriers and Bridges to the Renewal of Ecosystems and Institution*. New York: Columbia University Press.

Harris, L.D., and P.B. Gallagher. 1989. New initiatives for wildlife conservation: The need for movement corridors. In *Preserving Communities and Corridors.* G. Mackintosh, ed. Washington, D.C.: Defenders of Wildlife, 11–34.

Hilborn, R. 1992. Can fisheries agencies learn from experience? *Fisheries* 17, 6–14.

Hilborn, R., C.J. Walters, and D. Ludwig. 1995. Sustainable exploitation of renewable resources. *Annual Review of Ecology and Systematics* 26, 45–67.

Holling, C.S. 1978. *Adaptive Environmental Assessment and Management*. Chichester, U.K.: John Wiley & Sons.

Irwin, L.L., and T.B. Wigley 1993. Toward and experimental basis for protected forest wildlife. *Ecological Applications* 3, 213–217.

Kiker, C.F., J.W. Milon, and A.W. Hodges. 2001. Adaptive learning for science-based policy: The Everglades restoration. *Ecological Economics* 37, 403–416.

Kohm, K.A., and J.F. Franklin. 1997. Introduction. In *Creating Forestry for the 21st Century: The Science of Ecosystem Management.* K.A. Kohm and J.F. Franklin, eds. Washington, D.C.: Island Press, 1–5.

Lee, K.N. 1993. *Compass and Gyroscope: Integrating Science and Politics for the Environment*. Washington, D.C.: Island Press.

Mace, R.K., J. Waller, T. Manley, L.J. Lyon, and H. Zuring. 1996. Relationships among grizzly bears, roads, and habitat in the Swan Mountains, Montana. *Journal of Applied Ecology* 33, 1395–1404.

McLain, R.J., and R.G. Lee. 1996. Adaptive management: Promises and pitfalls. *Environmental Management* 20, 437–448.

McNamee, K. 2002. From wild places to endangered spaces: A history of Canada's national parks. In *Parks and Protected Areas in Canada: Planning and Management*. 2nd ed. P. Dearden and R. Rollins, eds. Dons Mills, Ont.: Oxford University Press, 21–50.

Morgan, M.G., and M. Henrion. 1990. *Uncertainty: A Guide to Dealing with Uncertainty in Quantitative Risk and Policy Analysis*. Cambridge, U.K.: Cambridge University Press.

NPS [National Park Service]. 2000. *Management Policies 2001.* Washington, D.C.: NPS.

———. 2002. Winter use plans: Yellowstone and Grand Teton National Parks and John D. Rockefeller, Jr., Memorial Highway. On-line at www.nps.gov/grte/winteruse/intro.htm.

National Research Council. 2002a. Ecological dynamics on Yellowstone's Northern Range: The report of the National Academy of Sciences. Chapter 5: Conclusions and recommendations. *Yellowstone Science* 10, 3–11.

———. 2002b. *The Missouri River Ecosystem: Exploring the Prospects for Recovery*. Washington, D.C.: National Academy Press.

Parks Canada. 2001. Record of 2001 Forum. Appendix B: Discussion paper: Working towards a strategy for human use management in Banff National Park. On-line at www.worldweb.com/ParksCanada-Banff/management_planning/record_of_2001_Forum/AppendixBe.htm.

Parma, A.M., and the NCEAS Working Group on Population Management. 1998. What can adaptive management do for our fish, forest, food, and biodiversity? *Integrative Biology* 1, 16–26.

Peterman, R.M. 1977. Graphical evaluation of environmental management options: Examples from a forest-insect pest system. *Ecological Modelling* 3, 133–148.

Peterman, R.M., and C.N. Peters. 1998. Decision analysis: Taking uncertainties into account in forest resource management. In *Statistical Methods for Adaptive Management Studies.* Land Management Handbook no. 42. V. Sit and B. Taylor, eds. Victoria: Research Branch, British Columbia Ministry of Forestry, 105-127.

Prato, T. 2000. Multiple attribute Bayesian analysis of adaptive ecosystem management. *Ecological Modelling* 133, 181–193.

———. 2003. Adaptive management of large rivers with special reference to the Missouri River. *Journal of the American Water Resources Association* 39, 935–946.

———. 2005. Bayesian adaptive management of ecosystems. *Ecological Modeling* 183, 146–156.

Sklar, F.H., H.C. Fitz, Y. Wu, R. Van Zee, and C. McVoy. 2001. The design of ecological landscape models for Everglades restoration. *Ecological Economics* 37, 379–401.

Smith, A.D.M., and C.J. Walters. 1981. Adaptive management of stock recruitment systems. *Canadian Journal of Fisheries and Aquatic Sciences* 38, 690–703.

Smith, G.R. 1997. Making decisions in a complex and dynamic world. In *Creating Forestry for the 21st Century: The Science of Ecosystem Management.* K.A. Kohm and J.F. Frank-

lin, eds. Washington, D.C.: Island Press, 419–435.
Turoff, M., and H. Linstone, eds. 2002. *The Delphi Method: Techniques and Applications.* On-line at www.is.njit.edu/pubs/delphibook/.
U.S. Army Corps of Engineers and South Florida Water Management District. 2000. *Master Program Management Plan, Comprehensive Everglades Restoration Plan.* West Palm Beach, Fla.: South Florida Water Management District.
U.S. Fish and Wildlife Service. 2003. *Grizzly Bear Recovery, Overview and Update.* On-line at http://mountain-prairie.fws.gov/endspp/grizzly/.
———. 2005. *Grizzly Bear Recovery, Northern Continental Divide Ecosystem.* On-line at http://mountain-prairie.fws.gov/species/mammals/grizzly/.
U.S. Geological Survey. 2004. *Northern Continental Divide Ecosystem (NCDE) Objectives.* Northern Rocky Mountain Science Center. On-line at http://nrmsc.usgs.gov/.
Walters, C.J., and R. Hilborn. 1978. Ecological optimization and adaptive management. *Annual Review of Ecology and Systematics* 9, 157–188.
Walters, C.J., and C.S. Holling. 1990. Large-scale management experiments and learning by doing. *Ecology* 71, 2060–2068.
Walters, C. 1996. *Adaptive Management of Renewable Resources.* New York: Macmillan and Co.
Walters, C.J., and R. Green. 1997. Valuation of experimental management options for ecological systems. *Journal of Wildlife Management* 61, 987–1006.
Wilhere, G.F. 2002. Adaptive management in habitat conservation plans. *Conservation Biology* 16, 20–29.
Wondolleck, J.M., and S.L. Yaffee. 2000. *Making Collaboration Work: Lessons from Innovation in Natural Resource Management.* Washington, D.C.: Island Press.
Woodley, S. 2002. Planning and managing for ecological integrity in Canada's national parks. In *Parks and Protected Areas in Canada: Planning and Management.* 2nd ed. P. Dearden and R. Rollins, eds. Dons Mills, Ont.: Oxford University Press, 97–114.

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