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An Adaptive-Management Framework for Optimal Control of Hiking Near Golden Eagle Nests in Denali National Park

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Abstract: *Unintended effects of recreational activities in protected areas are of growing concern. We used an adaptive-management framework to develop guidelines for optimally managing hiking activities to maintain desired levels of territory occupancy and reproductive success of Golden Eagles (*Aquila chrysaetos*) in Denali National Park (Alaska, U.S.A.). The management decision was to restrict human access (hikers) to particular nesting territories to reduce disturbance. The management objective was to minimize restrictions on hikers while maintaining reproductive performance of eagles above some specified level. We based our decision analysis on predictive models of site occupancy of eagles developed using a combination of expert opinion and data collected from 93 eagle territories over 20 years. The best predictive model showed that restricting human access to eagle territories had little effect on occupancy dynamics. However, when considering important sources of uncertainty in the models, including environmental stochasticity, imperfect detection of hares on which eagles prey, and model uncertainty, restricting access of territories to hikers improved eagle reproduction substantially. An adaptive management framework such as ours may help reduce uncertainty of the effects of hiking activities on Golden Eagles.*

Keywords: fluctuating populations, human disturbance, multistate site occupancy models, risk analysis, severe uncertainty, structured decision making

Un Marco de Referencia de Manejo Adaptativo para el Control Óptimo del Excursionismo en el Parque Nacional Denali

Resumen: *Los efectos no planeados de las actividades recreativas en áreas protegidas son de creciente preocupación. Utilizamos un marco de manejo adaptativos para desarrollar directrices para el manejo óptimo de actividades de excursionismo para mantener niveles deseables de ocupación territorial y éxito reproductivo de Águilas Doradas (*Aquila chrysaetos*) en el Parque Nacional Denali (Alaska, E. U. A). La decisión de manejo fue restringir el acceso humano (excursionistas) a determinados territorios de anidación para reducir la perturbación. El objetivo de manejo fue minimizar las restricciones a los excursionistas y mantener el desempeño reproductivo de águilas por encima de algún nivel especificado. Basamos nuestro análisis de decisiones en modelos predictivos de la ocupación de sitios por águilas desarrollados mediante*

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una combinación de opinión de expertos y datos recolectados en 93 territorios de águilas durante 20 años. El mejor modelo predictivo mostró que la restricción de acceso humano a territorios de águilas tuvo poco efecto sobre la dinámica de ocupación. Sin embargo, cuando consideramos fuentes importantes de incertidumbre en los modelos, incluyendo estocasticidad ambiental, detección imperfecta de conejos depredados por águilas e incertidumbre del modelo, la restricción del acceso de excursionistas a territorios mejoró la reproducción de águilas sustancialmente. Un marco de referencia de manejo adaptativo como el nuestro puede ayudar a reducir la incertidumbre de los efectos de actividades de excursionismo sobre las Águilas Doradas.

Palabras Clave: análisis de riesgo, incertidumbre severa, modelos de ocupación de sitios con múltiples estados, perturbación humana, poblaciones fluctuantes, toma de decisiones estructurada

Introduction

The effects on protected areas of recreational activities such as hiking and mountain biking are a growing concern (Taylor & Knight 2003; McGowan & Simons 2006). National parks in the United States often attract millions of visitors every year, which can have a dramatic effect on wild animals (hereafter wildlife) (e.g., Taylor & Knight 2003; McGowan & Simons 2006). In some cases these effects are easy to identify (e.g., vehicle collisions with wildlife [Sullivan et al. 2004]), whereas in other cases the effects may be more subtle. For instance, anthropogenic disturbances, such as biking and hiking, can induce energetic costs (e.g., stress, flushing) and affect animal behavior (e.g., decrease in nest attendance, avoidance of otherwise suitable areas, Steidl & Anthony 2000; Weimerskirch et al. 2001; Taylor & Knight 2003). Restricting hikers' access to certain areas may reduce the effects of human activities on wildlife. Although protecting natural resources is one of the primary functions of national parks (Fancy et al. 2009), managers also are mandated to maximize the positive experiences of visitors (Organic Act 1916). Restricting access to hiking trails may result in costs to the parks, for instance, by turning away visitors or otherwise reducing activities of social and economic importance to the region.

The development of new decision tools and an associated modeling framework may help managers address the problem of potentially conflicting objectives. We used a structured decision-making framework (e.g., Peterman & Anderson 1999; Williams et al. 2002; Martin et al. 2009a; Martin et al. 2010a) to develop recommendations for management of hiking to protect Golden Eagles (*Aquila chrysaetos*) in Denali National Park. Denali contains one of the largest reported nesting populations of Golden Eagles (McIntyre & Adams 1999), and park managers want to protect occupied nests from disturbance. Their objective is to minimize restrictions on hikers while maintaining reproductive success of eagles above some specified level. Our working group consisted of scientists and personnel charged with park management (all of whom are coauthors of this paper). Managers identified management objectives and potential actions. Scientists, including experts on Golden Eagles, monitoring, and structured-decision processes, developed models and applied optimization methods to derive decisions that were optimal with respect to the management objectives.

We used recent, dynamic, multistate-site occupancy models to describe the occupancy dynamics and reproduction of eagles in Denali (MacKenzie et al. 2009; Martin et al. 2009b; Martin et al. 2010b). We formalized mathematically the management objectives and devised three alternative models for predicting the effects of potential management actions on eagle occupancy and reproductive performance. The first model assumed no effect of hiking on occupancy and reproduction of Golden Eagles, the second assumed a moderate effect of hiking, and the third assumed a large effect of hiking. Using an optimization method, we identified sequences of decisions that would be optimal with respect to our management objectives and current state of knowledge (as expressed by mathematical models and estimates of eagle occupancy and reproduction). Finally, we identified several sources of uncertainty and explain how these sources of uncertainty can be incorporated into the decision process. In particular, we explain how adaptive management can be applied to reduce the uncertainty among our three predictive models (Williams et al. 2002).

Methods

Our study area was in the northeast section of Denali National Park, Alaska (United States), and covered 1800 km^2 (see McIntyre & Adams 1999 for details). The state of the system in year t is described by three state variables (s): number of unoccupied eagle territories ($N_t^{[0]}$), number of occupied eagle territories in which no young are produced ($N_t^{[[1]]}$), and number of eagle territories in which young are produced ($N_t^{[[2]]}$). The decision in year t corresponds to the number of sites that should be restricted to hikers (r_t). All these state variables correspond to the subset of potential territories that are accessible to hikers (25 in total) because only these territories are subject to possible hiking restrictions.

Objective Function

We sought to minimize the number of sites at which hiker access was restricted while maintaining the number of eagle territories with successful reproduction above some desired value (i.e., utility threshold [Martin et al. 2009*a*]) or equivalently to maximize the number of sites with unrestricted access while maintaining the number of sites with successful reproduction above a desired value (hereafter, we refer to this value as a utility threshold, τ).

We formalized our objective into a utility function

$$U_t = \left(N^{\mathrm{TOT}} - r_t\right) \times \alpha_t, \tag{1}$$

where U_t is the utility function at time t, which is a function of the total number of potential eagle territories that are accessible to hikers (N^{TOT}) and the number of territories to which hiker access is restricted at time t, (r_t). Thus, the term ($N^{\mathrm{TOT}} - r_t$) corresponds to the number of these sites to which access is unrestricted at time t. Parameter α_t is a penalty factor:

$$\alpha_t = 1/\left(1 + \exp\left\{a\left(\tau - E\left[N_t^{[2]} \mid N_{t-1}, H_t, r_t\right]\right)\right\}\right), \tag{2}$$

where τ is the utility threshold (i.e., the desired number of hiker-accessible nesting territories with successful reproduction) and $E[N_t^{[2]} \mid N_{t-1}, H_t, r_t,]$ is the expected number of these territories with successful reproduction at time t given the occupancy status at time t-1 (N_{t-1}) and hare index at time t (H_t), tallied before the management action (or decision, r_t) is implemented. The hare index corresponds to a primary eagle prey item and represents an environmental variable that is a determinant of eagle population dynamics. Parameter a is a steepness parameter and was set to 7 (see Supporting Information). According to Eq. 2, if $E[N_t^{[2]}] = \tau$, then α_t is 0.5; if $E[N_t^{[2]}] \ll \tau$, then α_t approaches 0; and if $E[N_t^{[2]}] \gg \tau$, then α_t is 1.0 (Supporting Information). We set the value of τ at the average number of hiker-accessible territories with successful reproduction for the last 20 years because it was considered a reasonable target by park managers (i.e., $\tau = 8$).

We used an optimization algorithm to identify the optimal decision, which we defined as actions that maximize

$$\lim_{T \to \infty} \frac{1}{T} \sum_{t=0}^{T} U_t, \tag{3}$$

where T is a specified time horizon. We refer to Eq. 3 as the average return which can be viewed as the cumulative number of nesting territories with no hiking restrictions over all years of the time horizon, penalized for the degree to which the number of expected successful nests was $\leq\tau$. We considered an infinite time horizon and used a discount factor close to 1 ($\delta = 0.999999$) so the solution is close to the nondiscounted case.

Models of System Behavior

We developed a dynamic multistate site-occupancy model for the territories that were potentially accessible to hikers (absent management restrictions). This general model linked restrictions of access to nesting territories to the dynamics of territory occupancy of eagles in Denali.

$$\begin{aligned} N_t^{[s]} = {} & \frac{N_{t-1}^{[0]}}{N^{\mathrm{TOT}}}\left[r_t\pi_{\mathrm{R}}^{0s} + (N^{\mathrm{TOT}} - r_t)\pi_{\mathrm{NR}}^{0s}\right] \\ & + \frac{N_{t-1}^{[1]}}{N^{\mathrm{TOT}}}\left[r_t\pi_{\mathrm{R}}^{1s} + (N^{\mathrm{TOT}} - r_t)\pi_{\mathrm{NR}}^{1s}\right] \\ & + \frac{N_{t-1}^{[2]}}{N^{\mathrm{TOT}}}\left[r_t\pi_{\mathrm{R}}^{2s} + \left(N^{\mathrm{TOT}} - r_t\right)\pi_{\mathrm{NR}}^{2s}\right], \end{aligned} \tag{4}$$

where ($N_t^{[s]}$) is the number of territories in state (s), N^{TOT} is fixed, π_{R}^{qs} is the transition probability from state q at time t to state s at time $t + 1$, R indicates this transition probability pertains to sites for which hiker access is restricted, and NR is the transition probability for the sites with unrestricted access. The implicit assumption of this model is that the number of restrictions is chosen and that restrictions are randomly assigned to the sites. It is possible to use a nonrandomized control in which restrictions are assigned to sites in specific states, but one of the benefits of the method described above is that one does not need to know the current occupancy and reproductive status of territories before making a decision. However, the occupancy and reproductive success from the previous season are assumed to be known. Here, the number of sites in state 2 (i.e., occupied with successful reproduction) at time t is obtained by subtraction.

$$N_t^{[2]} = \mathrm{N}^{\mathrm{TOT}} - \left(N_t^{[0]} + N_t^{[1]}\right). \tag{5}$$

Transition probabilities, π_{R}^{qs}, and π_{NR}^{qs}, are key parameters driving occupancy dynamics as a function of management actions. These parameters correspond to a multinomial parameterization; however, Martin et al. (2009b) used the conditional binomial parameterization to estimate the parameters from their empirical data. There is a direct correspondence between the multinomial and conditional binomial parameterizations (MacKenzie et al. 2009).

$$\begin{bmatrix} 1 - \psi_{t+1}^{[0]} & 1 - \psi_{t+1}^{[1]} & 1 - \psi_{t+1}^{[2]} \\ \psi_{t+1}^{[0]}\left(1 - R_{t+1}^{[0]}\right) & \psi_{t+1}^{[1]}\left(1 - R_{t+1}^{[1]}\right) & \psi_{t+1}^{[2]}\left(1 - R_{t+1}^{[2]}\right) \\ \psi_{t+1}^{[0]} R_{t+1}^{[0]} & \psi_{t+1}^{[1]} R_{t+1}^{[1]} & \psi_{t+1}^{[2]} R_{t+1}^{[2]} \end{bmatrix} = \begin{bmatrix} \pi_t^{00} & \pi_t^{10} & \pi_t^{20} \\ \pi_t^{01} & \pi_t^{11} & \pi_t^{21} \\ \pi_t^{02} & \pi_t^{12} & \pi_t^{22} \end{bmatrix}, \tag{6}$$

where $\psi_{t+1}^{[m]}$ is the probability that a nesting area is occupied by a Golden Eagle in year t+1 given that the area was in state m in year t ($m = 0$, unoccupied; $m = 1$, occupied with unsuccessful reproduction; $m = 2$, occupied with successful reproduction), and R_{t+1}^{m} is the probability of successful reproduction at a nesting area in year t+1 given that the area was in state m in year t and is occupied in year t+1 (MacKenzie et al. 2009; Martin et al. 2009*b*).

Martin et al. (2009*b*) found some evidence that potential human disturbance (potential human disturbance was assessed on the basis of accessibility of nest sites to hikers, see Martin et al. 2009*b* for details) and the abundance of snowshoe hares (*Lepus americanus*) (as measured by an abundance index), may affect the dynamics of territory occupancy of eagles in Denali. Snowshoe hares are a primary prey item for eagles, especially just before incubation and during incubation, but other species are taken during the late incubation and nestling periods (McIntyre & Adams 1999). Hence, probabilities $\psi_{t+1}^{[m]}$ and $R_{t+1}^{[m]}$ were modeled as linear-logistic functions of the index of hare abundance and human disturbance. For instance,

$$\mathrm{logit}\left(\psi_{t+1}^{[m]}\right) = \beta_{\mathrm{INT}} + \beta_{\mathrm{HARE}} \times \mathrm{HARE}_t + \beta_{\mathrm{DIST}} \times \mathrm{DIST} \quad (7)$$

(derived from Martin et al. [2009*b*]), where β_{INT} is the intercept, β_{HARE} is the slope for the relation between logit ($\psi_{t+1}^{[m]}$) and the index of hare abundance in year t (HARE_t), and β_{DIST} is a parameter that accounts for the binary effect of potential human disturbance at a territory (DIST = 0, low levels of disturbance [i.e., access to the territory restricted]; DIST = 1, high potential level of disturbance [i.e., access to territory not restricted], see Martin et al. 2009*b* for details). We then used Eq. 6 to derive π^{qs} on the basis of parameters $\psi_{t+1}^{[m]}$ and $R_{t+1}^{[m]}$. We obtained π_{R}^{qs} by setting DIST to 0 in Eq. 6, whereas we obtained π_{NR}^{qs} by setting DIST to 1.

Martin et al. (2009*b*) used historical data to evaluate the effect of human disturbance on the occupancy dynamics and reproduction of eagles. The goal of their analysis was to parameterize models such as the one described in Eq. 4. However, Martin et al. (2009*b*) based their analyses on historical data that were not collected with the objective of discriminating among different hypotheses about effects of potential management actions. Therefore, there remained substantial uncertainty about system responses to management actions. To account for model uncertainty (Williams et al. 2002; Martin et al. 2010*a*), we developed three models with similar structures (Eqs. 4–6) but different parameter values.

Experts adjusted the values of the parameters used in Martin et al. (2009*b*) on the basis of their knowledge of the system. In model 1, there was no effect of human activities on occupancy dynamics of eagles. Thus, we adjusted the parameters of this model to remove the disturbance effect by setting $\beta_{\mathrm{DIST}} = 0$ in the linear-logistic relations, which defined both R_{t+1}^{m} and ψ_{t+1}^{m}. We considered model 2 the most realistic scenario (expert opinion), and this model portrayed a moderate effect of disturbance on eagle reproduction. Model 3 reflected a substantial effect of human activities on eagle reproduction. Parameter values for sites with and without disturbance are presented in Fig. 1 for all three models.

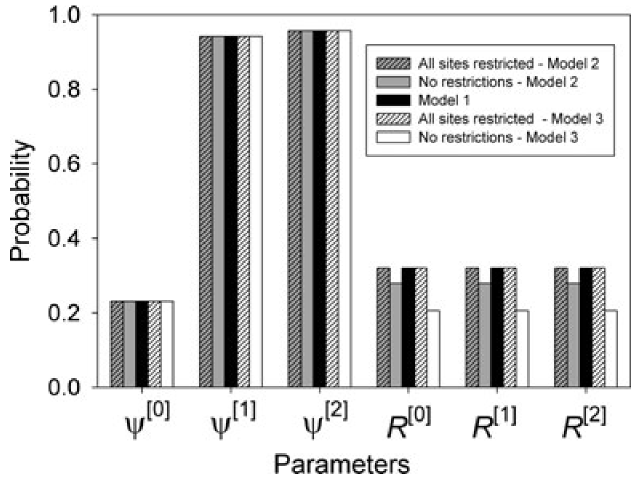

Figure 1. Values of transition probabilities for the three models of the effects of hikers on Golden Eagles: model 1, no effect of hikers on Golden Eagles; model 2, moderate effect; model 3, large effect of hikers on eagles (ψ_{t+1}^{m}, probability of a nesting area being occupied by Golden Eagles in year t+*1 given that it was in state* m *in year* t*;* m = *0, unoccupied;* m = *1, occupied without successful reproduction; or* m = *2, occupied with successful reproduction;* R_{t+1}^{m}, *probability of successful reproduction occurring at a nesting area in year* t+*1 given that it was in state* m *in year* t *and is occupied in year* t+*1; hash marks, parameter values for the territories to which hiker access is restricted; no hash marks, parameter values for territories to which hiker access is not restricted). Estimates of* ψ_{t+1}^{m} *and* R_{t+1}^{m} *are based on expert opinion and estimates from Martin et al. (2009*b*). Parameters* ψ_{t+1}^{m} *and* R_{t+1}^{m} *were assumed to be affected by hare abundance (see Eq. 6), for this figure Hare index was zero.*

Optimization

We used stochastic dynamic programming to find the sequences of decisions that were optimal with respect to our objective and models. We solved the problem for an infinite time horizon by using policy iteration (Miranda & Fackler 2002) within the software MDPSOLVE (under development by Paul Fackler). This software package is in MATLAB programming language, which is used to solve general discrete-state and discrete-action dynamic programming problems.

Simulation Scenarios

At least 93 eagle territories have been found in Denali since 1988. We focused our analyses on the 25 territories believed by biologists to have the potential to be disturbed by hikers (C. M., personal observation).

We simulated several management scenarios to evaluate their effects on eagle reproduction. First, we considered scenarios in which hikers could access all or none of the territories. A large difference in the accumulated return (i.e., the average utility, $\overline{U}_t$, Eq. 3) between scenarios with no restrictions and maximum restrictions would mean the ability to significantly improve eagle reproduction by restricting access to eagle territories existed.

Addressing Uncertainty

Hare abundance fluctuates greatly in our study area, and reproduction of Golden Eagles is believed to be affected by changes in hare abundance (McIntyre & Adams 1999; Krebs et al. 2001; Martin et al. 2009*b*). Hare abundance can be considered either a state variable or a random environmental variable. If hare abundance is treated as a state variable, at each decision step the optimal decision is a function of hare abundance and values of the other state variables. If hare abundance is treated as a random environmental variable, then the abundance is not known at the time of the decision and the fluctuating abundance is a source of extra variation (i.e., noise) in the system predictions. We treated hare abundance as a random state variable, but our approach did not require a model of hare dynamics because in this case hare abundance was assumed to be independent from one year to the next. Thus, we assumed the current abundance of hares was known (without error) at the time of the decision and derived an optimal strategy that was a function of hare abundance and eagle occupancy. More specifically, we assumed the occupancy and reproductive success from the previous season was known (but unknown for the current season). In this case the optimal decision depended on the value of each state variable ($N_t^{[0]}, N_t^{[1]}, N_t^{[2]}$) and on hare abundance. Of course, hare abundance varies from year to year, and decisions can be based on $N_t^{[0]}, N_t^{[1]}, N_t^{[2]}$, and observed hare abundance for that particular year. This approach allowed us to use information about annual hare abundance without explicitly modeling hare abundance over time.

We simulated the effects of implementing the optimal sequence of decisions for this optimization analysis. We examined the utility function (U_t), the number of occupied sites with successful reproduction ($N_t^{[2]}$), and the number of sites to which hiker access was restricted (r_t) over time.

It is possible to explicitly account for model uncertainty by considering multiple models in the optimization process (e.g., Williams et al. 2002). In our application, we considered models 1, 2, and 3. Models 1 and 3 reflect two possible extremes. Model 1 represents a scenario in which hikers have no effect on eagles, whereas model 3 represents a scenario in which hikers have strong negative effect on eagles. By incorporating these models into the optimization algorithm, uncertainty can be reduced by implementing the optimal decisions and then updating model weights with Bayes' theorem through a comparison of predicted and observed system responses (Williams et al. 2002). We implemented a passive adaptive-optimization algorithm (sensu Williams et al. 2002).

Changes in the Utility Threshold

To examine how changes in τ can affect decisions, we determined the average utility over 25,000 time steps. We removed the first 50 values to reduce the effect of the initial conditions ($\overline{U}_t$) and report average restrictions on hiker access to eagle territories and the average number of successful territories with $\tau = 5$ and $\tau = 11$. Recall that τ is the desired number of nesting territories, of the 25 territories potentially accessible to hikers, at which successful reproduction occurs.

Results

Under model 2 (most realistic), there was little difference in occupancy dynamics associated with not restricting hiker access to any sites, restricting access to all sites, and following the optimal sequence of decisions (Table 1). In contrast, there were substantial differences in occupancy dynamics among the three sets of restrictions in the scenario in which hiker access had a large effect on occupancy and reproduction of eagles (model 3, Table 1). The optimal decisions (i.e., number of sites to which access should be restricted) depended mostly on the number of sites unoccupied before making the decision. This was because in our application parameters $R_{t+1}^{[1]} = R_{t+1}^{[2]} = R_{t+1}^{[3]}$ (Fig. 1), and we found that the number of sites at which to restrict access increased as the number of unoccupied sites increased. We also found that the optimal number of sites at which to restrict access was higher when hare abundance was low than when hare abundance was high.

We plotted simulation results of the passive adaptive approach to optimization to illustrate the implementation of adaptive management as a means of dealing with model uncertainty. Simulations of the changes in weights for each model showed that the rate of learning was slow given the initial model weights considered. If the "true" model was one of no effect of hikers on eagles (model 1), the optimal decisions would ultimately converge on leaving all sites unrestricted (Figs. 2d–f). In contrast, if the true model was that of a large effect (model 3), the optimal decisions converged to the decisions obtained from the nonadaptive optimization for the large effect model (model 3, Figs. 2a–c).

Moderate changes in the utility threshold (τ) from the original value selected by managers (i.e., $\tau = 8$) led to different decisions and outcomes. For instance, setting $\tau = 5$ led to an average utility ($\overline{U}_t$) of 18.4 (SD 6.4), an

Table 1. Summary of average utility, average number of territories to which hiker access is restricted, and average number of territories with successful reproduction for simulations under model 2 (most realistic, moderate effect of hikers on Golden Eagles) and model 3 (greatest effect of hikers on eagle reproduction).

Model[a]	*Average utility (SD)*[b]	*Average no. of territories to which hiker access is restricted (SD)*[c]	*No. of territories with successful reproduction (SD)*[d]
Model 2 optimal	5.8 (9.0)	17.7 (9.2)	7.8 (2.9)
Model 2 no restrictions	4.6 (8.8)	0	7.2 (3.0)
Model 2 max restrictions	0	25	8.1 (3.1)
Model 3 optimal	3.7 (7.5)	20.7 (7.4)	7.6 (2.6)
Model 3 no restrictions	2.5 (7.5)	0	5.5 (2.8)
Model 3 max restrictions	0	25	8.1 (3.1)

[a]*For each model we considered three scenarios: one in which the simulation followed the optimal decisions under the specified model (optimal, in this case hare treated as a known state variable), one in which no restrictions were ever implemented (no restrictions), and one in which all biking activities were restricted at all territories (max restrictions).*
[b]*Average utility ($\overline{U}_t$) over 25,000 time steps (first 50 values removed to reduce effect of initial conditions).*
[c]*Average number of territories to which hiker access is restricted over 25,000 time steps (first 50 values removed to reduce effect of initial conditions).*
[d]*Average number of successful territories over 25,000 time steps (first 50 values removed to reduce effect of initial conditions).*

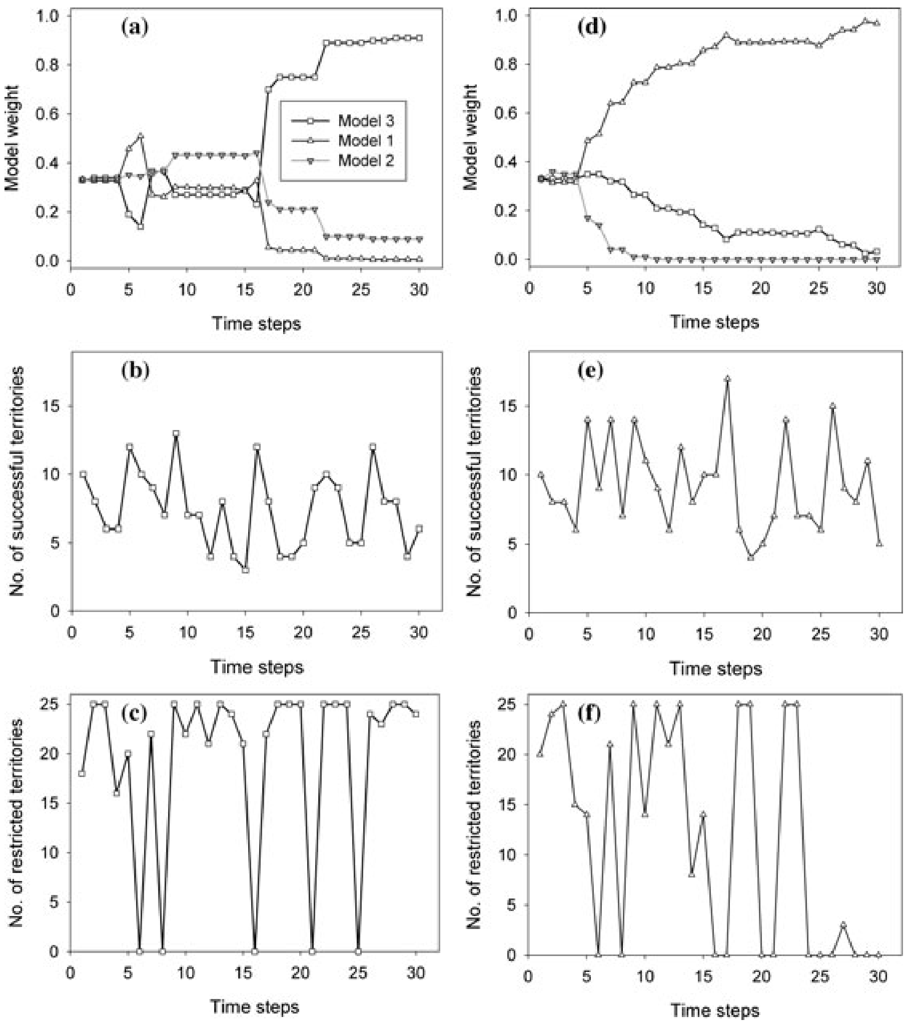

Figure 2. Consequences of following the optimal decisions about restricting hiker access to nesting territories of Golden Eagles obtained from a passive optimization algorithm, assuming the true model predicts (a, b, c) a large effect (model 3) of hikers on eagles and assuming the true model predicts (d, e, f) no effect of hikers on eagles (model 1) ([a,d], change of model weights over time for the three models under consideration; [b,e] number of territories with successful reproduction; [c,f] number of territories at which hiking was restricted). In this example, we assigned equal initial weights to each model. Hare abundance was treated as a random variable in the simulations. Each line corresponds to a single realization of the simulation analysis over 30 years.

average number of sites to which access was restricted of 5.6 (SD 5.7), and an average number of territories in which breeding was successful of 6.0 (SD 2.7). Setting τ to 11 led to an average utility of 1.9 (SD 6.06), an average number of sites to which access was restricted of 23 (SD 6.3), and an average of number of territories in which breeding was successful of 7.9 (SD 2.7). Thus, as τ increased the average utility decreased, whereas the number of territories to which access was restricted and number of successful territories increased. Setting τ to 22 territories led to an average utility of 0.0 no matter what decisions were made.

Discussion

Control of the Managed System

In the most realistic model (model 2, combination of empirical estimates and expert opinion) for the optimal control of hiking activities in Denali National Park, the potential management actions (i.e., restriction of hiker access to nesting territories) had only a small effect on the occupancy dynamics of Golden Eagles in Denali National Park. For instance, there were small differences in the average utility between decisions in which hiker access to nesting territories was unrestricted and decisions in which hiker access to all nesting territories was restricted (maximum restrictions, Table 1). In contrast to the most realistic scenario, occupancy and reproduction of eagles when hikers had a large effect on eagle occupancy and reproduction (model 3) was substantially more affected by access restrictions (Table 1). By including model 3 in the adaptive optimization analyses, we were able to account for the probability that hikers have a dramatic effect on eagles. Because model 3 was the only model that had substantial effects on the occupancy and reproduction of eagles, we used this model to illustrate several points related to the optimal control of hiking in Denali.

Hare abundance is an important driver of the reproductive success of Golden Eagles; thus, it may be important to estimate this variable accurately in order to reduce errors associated with partial observability (McIntyre & Adams 1999; Williams et al. 2002; Martin et al. 2009*a*). The optimal number of sites at which to restrict access was higher when hare abundance was low than when hare abundance was high. Treating hare abundance as a random state variable may be particularly useful when there is substantial environmental variation in the system associated with a key variable that can be measured, such as hare abundance.

Adaptive Management

Model or structural uncertainty is a substantial source of uncertainty in the context of natural resource management. We initially considered three models that formalized three hypotheses about effects of hiker access on occupancy dynamics of Golden Eagles. Adaptive optimization allowed us to identify the optimal decisions given this uncertainty. Simulations of the adaptive process showed that model uncertainty can be reduced over time. If hikers do not affect eagle reproduction substantially, the adaptive process should ultimately identify a no-restrictions sequence of decisions as optimal (Figs. 2d–f). By including a third model that assumed a large effect of hikers on eagles, we could ensure that hiker access was restricted sufficiently if statistical analyses combined with expert opinion failed to account for a large effect of recreational activities on eagle reproduction (Figs. 2a–c).

Sensitivity of Decisions and Outcomes to Changes in the Utility Threshold

As we increased the desired number of successful territories (the utility threshold), the optimal decisions led to an increase in both the average number of territories to which hiker access should be restricted and the average number of successful nesting territories. When the utility threshold was set at 22, the utility was 0 regardless of which decisions were made. Thus, if the value of the selected utility threshold falls outside the range of values that can be achieved through management, or if this value can be achieved regardless of decision, then all decisions will lead to an identical average utility.

General Applicability of the Approach

We considered a specific management problem in one national park. However, we believe this case is relevant to many situations in which there is a desire to maintain both recreational opportunities in natural areas and elements of the ecosystem. We used a combination of empirical estimates from historical data and expert opinion to develop our models and believe this approach can be applied in other situations in which few empirical data are available. In fact, we believe models based entirely on expert opinion are nearly always preferable to delaying decisions while more data are collected. Uncertainty of system responses to management complicates decision making. It may be informative to consider alternative models in which a given management action does or does not have large effects on the managed system. It is possible that adaptive management will be undertaken only if the optimal decisions match a priori expectations (or preferred actions). This is why it is critical that the objective function (which should be developed at the beginning of the structured decision-making process) appropriately capture the objectives of the key players in the decision-making process (e.g., stakeholders and managers). Even if the optimal action is not implemented, it is still possible to reduce model uncertainty and thereby learn by updating the model weights with Bayes' theorem (Williams et al. 2002).

Adaptive management has been discussed for decades (Walters 1986; Williams & Johnson 1995; Nichols et al. 2007; Williams et al. 2007), but it has rarely been implemented rigorously. Our application of adaptive-management principles to a specific case study in a single national park emphasizes the flexibility of this approach. The underlying logic of adaptive management as a means of addressing uncertainty in decision making is not restricted to specific spatial scales or types of recurrent decisions. We hope our engagement of Denali National Park personnel in this process will encourage similar collaborations to achieve management decisions that are both transparent and scientifically defensible.

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Supporting Information

Illustration of relation between the expected number of successful territories and the utility factor is available as part of the online article (Appendix S1). The authors are responsible for the content and functionality of these materials. Queries (other than absence of the material) should be directed to the corresponding author.

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