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Invited Paper

Climate Change, Uncertainty, and Natural Resource Management

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ABSTRACT Climate change and its associated uncertainties are of concern to natural resource managers. Although aspects of climate change may be novel (e.g., system change and nonstationarity), natural resource managers have long dealt with uncertainties and have developed corresponding approaches to decision-making. Adaptive resource management is an application of structured decision-making for recurrent decision problems with uncertainty, focusing on management objectives, and the reduction of uncertainty over time. We identified 4 types of uncertainty that characterize problems in natural resource management. We examined ways in which climate change is expected to exacerbate these uncertainties, as well as potential approaches to dealing with them. As a case study, we examined North American waterfowl harvest management and considered problems anticipated to result from climate change and potential solutions. Despite challenges expected to accompany the use of adaptive resource management to address problems associated with climate change, we conclude that adaptive resource management approaches will be the methods of choice for managers trying to deal with the uncertainties of climate change. © 2011 The Wildlife Society.

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Most scientists and decision-makers now recognize that climate change has not only influenced the earth and its systems over the last few decades, but will also likely continue to do so into the intermediate and long-term future. Although there is a great deal of certainty that climate-induced changes will occur, predictions about the precise nature of those changes remain uncertain. Decision-makers in various disciplines are considering approaches to deal with this uncertainty. Managers of natural resource systems are accustomed to dealing with uncertainty, as knowledge of these systems and their dynamics is always limited. Thus, rather than treating climate change and its concomitant uncertainty as a novel phenomenon requiring new approaches to management, we argue for the application of existing approaches to managing in the face of uncertainty.

Adaptive management is an approach to decision-making developed for recurrent decisions in the face of uncertainty (e.g., Walters 1986; Williams et al. 2002, 2007). Adaptive management exploits the ability provided by recurrent decisions to learn about system responses and to reduce uncertainty associated with future decisions. We considered the use of adaptive management to deal with natural resource decision problems likely to be influenced by climate change. Although we do not view climate change as an entirely novel problem requiring completely new approaches to management, we do acknowledge its potential to exacerbate uncertainty. The prospects of system change and nonstationarity (see below), in particular, will likely require modifications to treatments of decision processes.

We focused on a specific class of natural resource decision problems influenced by climate change. We provide a framework for thinking about decision-making by outlining the components of a structured decision process. We outline the more specific process of adaptive management as one logical approach to dealing with uncertainty and trying to reduce it. Next we consider sources of uncertainty in natural resource management and consider how climate change is expected to exacerbate these uncertainties. In doing so, we suggest general approaches to dealing with these changing uncertainties in management.

We examined mid-continent mallard harvest management as a case study to illustrate the kinds of adaptations that might be useful for dealing with climate change. We focused on climate adaptation with respect to each of the components

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of a structured decision process and to the process of adaptive management. Finally, we considered some of the political, institutional, and technical challenges that we anticipate in applying the principles of structured decision-making and adaptive management to natural resource management in the face of increased uncertainty related to climate change.

CLASSES OF DECISION PROBLEMS DEALING WITH CLIMATE CHANGE

Climate change is a pervasive problem, and discussions of ways to deal with it when making decisions can easily become wide-ranging and unfocused. An initial broad classification of climate-induced decision problems can be useful in focusing discussion. One class of decision problem relevant to climate change involves actions that attempt to influence such change directly, such as a reducing energy use, reducing carbon emissions, and sequestering carbon. We did not consider problems in this class.

The other main class of problem instead focuses on decisions (e.g., about natural resources) that are themselves influenced by climate change. That is, conditional on the reality of climate change, how should resources be managed in the face of such change and its uncertainty? Within this general class, we can further subdivide decision problems into modification of existing management programs to adapt to climate change and development of entirely new management programs that would not be needed were it not for climate change. An example of the latter problem might be a species with range restricted to some key islands that is doing well and currently requires no active management, but is expected to lose its habitat to sea level rise. A new translocation program might be considered for this specific climate-induced problem. We did not consider this class of problem either and instead focus here on the modification of existing natural resource management programs to deal with climate change. Many natural resources and associated systems are actively managed currently, and we consider how such management may be modified and adapted to deal with climate change and its concomitant uncertainty. Adaptive management can be used to deal with problems in each of the listed classes; we focused on existing management problems simply to keep our discussion from ranging too widely.

ELEMENTS OF A STRUCTURED DECISION PROCESS

Existing programs of informed management are typically guided by a structured decision process and should thus include the following key elements: 1) objectives, 2) available management actions, 3) model(s) of system response to management, 4) monitoring program for system state variables and related quantities, 5) solution (e.g., optimization) algorithm. Objectives are simply a clear statement of what we hope to achieve by management. They should be developed jointly by all relevant stakeholders. Frequently, the objectives of multiple stakeholders differ, requiring trade-offs and compromise. Multiple objectives may be handled by use of a common currency or by imposition of constraints on maximization or minimization problems. Management interventions include the set of actions to be considered as a means of achieving objectives. Some actions, for example predator control, may be potentially effective, yet politically or socially unacceptable. Thus, stakeholder involvement is also important in identifying the set of actions to be considered. Specified objectives and potential actions are frequently viewed as the policy components of the structured decision-making framework.

Management requires an ability to predict the response of the managed system to the different management actions. Models provide such predictions. Mathematical models are a common management tool and contribute to transparency in specifying exactly what predictions lead to a particular decision. In many cases uncertainty about system responses to management is so great that managers consider the use of multiple models representing competing hypotheses. Monitoring provides a basis for comparing model-based predictions against what actually happens and thus for learning about which model is the best predictor. In addition, monitoring of system state variables (i.e., attributes of a system that are used to characterize system status or health; e.g., population size) provides estimates needed for state-specific decisions and for assessing the degree to which objectives are being attained. Solution algorithms provide a means of arriving at a decision, conditional on the other components of the decision process. Specifically, optimization algorithms provide a means of determining the best decision, given the objectives, available actions, model(s), and estimated system state.

ADAPTIVE MANAGEMENT

As noted, adaptive management is an approach to decision-making that was developed to deal with uncertainty when making recurrent decisions (e.g., Walters 1986; Williams et al. 2002, 2007). Adaptive management is a special kind of structured decision process, and, as such, it requires the elements we described. The initial set-up or deliberative phase of adaptive management requires substantial stakeholder involvement to define objectives and the management actions to be considered at each decision point (Williams et al. 2007). This phase also requires development of models predicting system response to management actions. A monitoring program is necessary to provide the initial assessment of system state and, subsequently, to discriminate among competing models and assess progress towards objectives. A solution algorithm is needed to determine the best decision based on the other elements.

The use of multiple models that make different predictions requires a corresponding set of credibility measures. These measures reflect the relative degree of faith in each member of the model set (each measure is constrained to the interval [0,1]), and they sum to one for all of the members of the model set. The measures are important to the decision process as they determine the degree to which each model's predictions are used to develop the decision. Specifically, models with larger credibility measures exert more influence in the decision. The initial credibility measures may be based on inferences from historical data, expert opinion, or even stakeholder judgment. However, after the initial decision is made, subsequent credibility measures evolve in response to the relative predictive abilities of the models, as reflected by comparison of model-based predictions with monitoring data (Williams et al. 2002). Specifically, credibility measures are formally updated using Bayes theorem, based on credibility measures from the previous decision point and the new information about the predictive ability of the models based on new monitoring data.

The iterative phase of adaptive resource management proceeds using the identified elements to make decisions. At each decision point, the solution algorithm is used to decide the action to take, based on the objectives, available actions, models and corresponding credibility measures, and estimated state of the system (from the monitoring program). The action taken drives the system to a new state. That new state is estimated via the monitoring program. In addition to providing information about system state for the next decision, this estimate is compared to model-based predictions, and the credibility measures are modified accordingly. Thus, at each decision point during the iterative phase, the objectives, available actions, and models remain static, with the estimated state of the system and the credibility measures changing at each time step.

As adaptive management proceeds through time, changing credibility measures reflect learning about which models provide better predictions about system response to management. These changing credibility measures produce changing model influences on decisions, reflecting the use of learning (adaptation) in management decision-making. In addition to this continual adaptation of decision-making based on what is learned about the system, so-called double-loop learning (Williams et al. 2007) provides additional opportunities to modify the process. At time periods typically longer than those of the iterative decision process, double-loop learning entails revisiting any or all components of the set-up phase of adaptive management. For example, at times it may be useful to revisit either the management objectives or the set of available actions. If none of the models consistently delivers good predictions, then the model set may be revisited as well. Finally, if the monitoring program is not providing sufficiently precise estimates of the key state variables, then it may require modification.

CLIMATE CHANGE AS A SOURCE OF UNCERTAINTY

Adaptive management, as described above, was developed explicitly to deal with uncertainty in natural resource management. Many different types of uncertainty exist, and there are numerous ways of classifying forms of uncertainty. Here we list and describe the 4 classes of uncertainty typically found in discussions motivating adaptive resource management (e.g., Johnson et al. 1993; Williams 1997; Williams et al. 2002, 2007). Rather than view climate change as a new class of uncertainty, we view it as a phenomenon capable of exacerbating the classes of uncertainty that we traditionally deal with via adaptive management. We discuss these potential influences of climate change on the sources of uncertainty typically considered in adaptive resource management, and we suggest general approaches to deal with them.

Environmental Variation

Environmental variation is a source of uncertainty well known to most biologists and managers and refers to the influence of environmental variables on system state variables (e.g., population size) and the vital rates (e.g., rates of survival, reproduction, and movement) that drive changes in the state variables. There are 2 basic approaches to incorporating environmental variation into model-based predictions, one more implicit and the other more explicit. Under the more implicit approach, models that predict system responses to management actions incorporate environmental variation by producing probabilistic predictions of system state variables and, sometimes, associated vital rates. That is, the model does not predict a specific value of a system state variable (or vital rate), but rather a distribution of possible values. One of the primary reasons for producing a range of possible predicted values is environmental variation that cannot be precisely anticipated (or perhaps even identified) at the time a prediction must be made.

If a specific environmental variable is recognized as an important driver of system dynamics, then it may be incorporated explicitly into a model. For example, in models of mallard population dynamics, mallard reproductive rate is modeled as a function of the number of ponds on key breeding grounds (Crissey 1969, Hammack and Brown 1974, Johnson et al. 1997). In the model, pond numbers in one year depend on pond numbers the previous year and rainfall (e.g., Pospahala et al. 1974, Johnson et al. 1997). The model predicts a distribution of possible pond numbers, leading to a distribution of numbers of young mallards produced (thus predictions are again probabilistic), because rainfall is uncertain. Uncertainty can be reduced for single-season predictions in cases where monitoring programs provide estimates of key state variables (e.g., pond numbers) influenced by dynamic environmental variables.

Model-based predictions thus incorporate environmental variation either implicitly, through the range of values of state variable predictions, or explicitly, as functional relationships between vital rates (e.g., rates of reproduction and survival) and environmental variables. In both cases, the traditional way of estimating such variation for incorporation into models is to investigate frequencies of historical values (e.g., of population size, ponds, rainfall) obtained from monitoring programs. The processes that drive environmental variation are assumed to be stationary, and distributions obtained from historical monitoring data are assumed to apply to the system into the indefinite future. Stated differently, environmental variation observed over the last 50 years is assumed to provide a reasonable characterization for the next 50 years.

The challenge of climate change is that changes in environmental variables may cause distributions based on the past to do a poor job of predicting the future. Indeed, one of the major modifications to management programs resulting from climate change will entail a shift in models of environmental

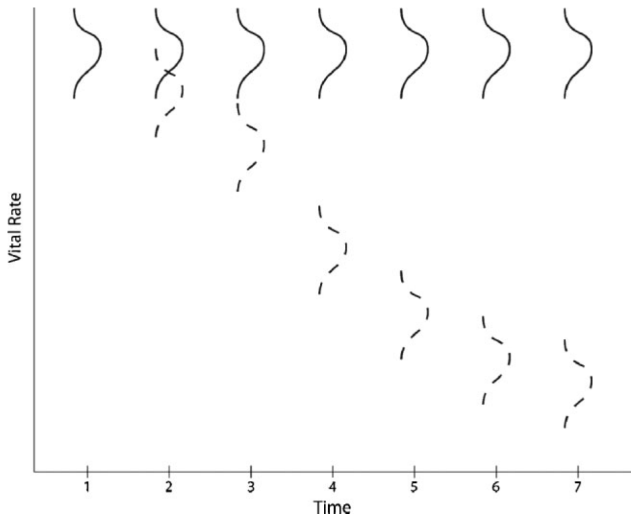

Figure 1. Depiction of 2 stochastic processes describing temporal variation in probability distributions underlying a hypothetical vital rate (e.g., annual survival probability) that varies as a function of environmental variation. The solid line distributions represent a stationary process near equilibrium. The vital rate is a random variable that can vary from time to time, but it does so according to a probability distribution that remains constant over time. The dashed line distributions represent a process that is not stationary but evolves with time. The vital rate follows a probability distribution at each time step, but the distribution itself changes over time with smaller values of the vital rate more likely as time goes on.

variation from stationary distributions to distributions that evolve through time (Milly et al. 2008). We anticipate using recent monitoring data on changes in environmental and state variables as a basis for developing models of temporal change. Thus, instead of viewing environmental variation in terms of distributions that are themselves static, managers will need to develop models that incorporate the evolution of these distributions over time (Fig. 1). Incorporating these evolving distributions into our models reflects a proactive approach to dealing with climate change.

Although we focused this discussion of climate change and environmental variation on models, we emphasize that we expect all of the components of decision processes to be potentially influenced by climate change, in general, and by its effects on environmental variation, in particular. For example, we anticipate that our objectives may evolve as climate change produces changes in habitat, and thus carrying capacity, for managed populations.

Partial Controllability

Partial controllability is a source of uncertainty that pertains to imprecision in the application of management actions. An example can be found in waterfowl harvest regulations. Specific hunting regulations are precise in the sense of specifying daily bag limits and season dates. However, if the exact same set of regulations was applied to the target population for 5 consecutive years, 5 different harvest rates would likely result. Managers cannot predict with certainty the harvest rates that will be produced by a specific set of regulations; instead harvest rates are best represented by a distribution of possible values (Johnson et al. 1997). As is the case for environmental variation, current models quantify this source of uncertainty using frequency distributions of harvest rates generated by identical sets of hunting regulations historically. In addition, harvest rate estimates from ongoing monitoring programs provide new estimates that are used to better specify these distributions. Nevertheless, the new estimates are assumed to have come from the same historical distributions, and these distributions are further assumed to apply into the indefinite future.

Climate change again poses a challenge, as it may affect the imprecision of our management actions. Using waterfowl harvest regulations as an example, climate change will likely induce changes in migration chronology and terminal wintering areas of birds, as well as possibly in behavior of hunters and resultant hunting pressure. Both kinds of change are predicted to produce changes in exposure of birds to hunting, and thus possible changes in harvest rates. As with environmental variation, management models that consider climate change will likely incorporate changes in distributions of harvest rates expected to result from a specific set of hunting regulations. Again, managers will need to rely on estimates from recent monitoring data to help predict the evolution of harvest rate distributions over time. Similar proactive approaches may be needed to deal with other forms of partial controllability influenced by climate change.

Partial Observability

Partial observability as a source of uncertainty acknowledges that researchers rarely observe nature directly, but instead are forced to estimate quantities of interest about natural systems. Counts of animals, for example, are nearly always characterized by 2 important sources of variation, geographic variation and detection probability (e.g., Lancia et al. 1994, 2005; Williams et al. 2002). Geographic variation is an issue because of our frequent interest in estimates of animal abundance that cover areas so large as to preclude a complete survey. Therefore, managers must select areas to survey in a way that permits inference about the areas not surveyed. Detectability refers to the reality that surveys of animals virtually always fail to detect all individual animals present in surveyed areas. Both of these sources of variation lead to uncertainty in estimates of animal state variables and vital rates. As with other sources of uncertainty, a consequence of estimation is that such quantities as population size or survival rate or harvest rate are not known exactly. Instead, managers must consider distributions of these quantities. In this case, the distributions do not reflect year-to-year variation in true underlying values, but instead reflect the range of possible values for a specific year. Thus, for a given year, estimation will indicate what values (e.g., of population size) are more and less probable. Partial observability is a source of uncertainty that characterizes virtually every quantity that is estimated from a monitoring program.

Climate change has the potential to influence partial observability. For example, duck population sizes are estimated annually by the Waterfowl Breeding Population and Habitat Survey conducted over key breeding grounds of North America (Smith 1995). Although survey strata are thought to have included most breeding ducks for many species historically, it is likely that climate change will induce shifts in breeding distribution patterns. If these shifts cause large numbers of birds to move to areas not included in current monitoring strata, then abundance estimates may represent changing proportions of the total populations of surveyed species. Such changes would result in this monitoring program producing increasingly biased estimates of population size. It is conceivable that the current strata of the Waterfowl Breeding Population and Habitat Survey could be changed, with expansions in some areas and possible contractions in others. At a minimum, frequent assessments of the adequacy of the spatial coverage of current monitoring programs seem warranted.

Phenological changes also have potential to influence partial observability and the ability of monitoring programs to provide unbiased estimates. United States Fish and Wildlife Service surveys for mourning doves (*Zenaida macroura*) are based on counts of birds along roadside transects in the spring of each year. In many locations of North America, most detections of doves are auditory. Avian singing behavior is influenced by pairing status and thus timing of the breeding season (e.g., Baskett et al. 1978), which is itself influenced by climate. Rapid climate change could conceivably produce changes in temporal patterns of singing behavior (e.g., Crick and Sparks 1999) and thus in detection probabilities. This possibility should lead to an increase in efforts to include inferences about detection probability in survey designs.

In summary, climate change has the potential to induce changes in distribution and behavior of wildlife over both space and time. Such changes have the potential to influence results of animal monitoring programs. The appropriate response to such changes is increased vigilance and frequent assessments of the adequacy of current monitoring programs in the face of climate change.

Structural Uncertainty

The final source of uncertainty is typically referred to as structural and concerns the models used to project the consequences of management actions on managed systems. Human understanding of many systems is so incomplete that managers admit multiple possibilities about how these systems respond to management. These different possibilities represent different hypotheses about the system and are developed as competing models. Instead of characterizing uncertainty and variation by a distribution of parameter values, as discussed with respect to the other 3 sources of uncertainty, managers try to capture structural uncertainty by use of a discrete set of models. As discussed above, each member of the model set is assigned a weight or credibility measure that reflects the degree of faith in that model. These weights are numbers between zero and one that sum to one for all members of the model set. Thus, the weights form a distribution that characterizes uncertainty about the predictive abilities of the different models. We have more faith in the models with larger weights, and these models have more influence in management decisions. Model weights evolve through time based on the degree of correspondence between model-based predictions and estimates from the monitoring programs.

Climate change has the potential to influence modeling and structural uncertainty in multiple ways. Here we focus on a major issue that we noted in the discussion of environmental variation, nonstationarity. Specifically, rather than viewing environmental variation as driven by a stationary process, managers must recognize that environmental variation is now driven by processes that themselves evolve over time. There are at least two approaches to dealing with this nonstationarity in modeling (also see Conroy et al. 2011). The first approach is more proactive and relies on the ability to identify the important climatic variables that drive system dynamics and to anticipate and model their change through time. In such cases, these important climatic variables can be incorporated as state variables in system models. System models would then include not only the biological state variables of specific management interest, but also the driver climatic variables that are themselves expected to change.

The other approach is more reactive and represents an attempt to deal with nonstationarity in situations where either the important climatic variables that drive system dynamics cannot be identified or else changes in climate variables identified as important cannot be adequately modeled. Under this approach, although managers may still seek objectives over long time horizons, long-term outcomes may be difficult or impossible to predict from a current model set because of changing climatic processes. In such cases, a pragmatic approach may be to implement policies that are robust or optimal over short-term time horizons (e.g., 5–10 yr). This approach essentially assumes system stationarity as an approximation to reality over each of a series of short time horizons, with the expectation of changing system models based on monitoring data, at the end of each series. This expectation of model change at the end of each time horizon emphasizes learning about system change, especially at the end of each series of short-term time horizons. This approach exploits double-loop learning, with frequent revisions of system models, as a pragmatic approach to dealing with climate change that cannot be adequately anticipated or modeled.

Sources of Uncertainty: Summary Comments

Climate change will likely influence each of the above sources of uncertainty with which managers of natural resources must deal. One appropriate management response to climate influences on 3 of these sources of uncertainty (i.e., environmental variation, partial controllability, structural uncertainty) involves modification of existing models used to predict system responses to management actions. These modifications will require new information supplied by monitoring programs, either as they exist now or, in some cases, as modified in specific ways to deal with climate change. Other management responses will involve vigilance and continued assessment of adequacy of the various decision process components (e.g., objectives, actions). The fourth source of uncertainty, partial observability, affects monitoring programs directly and will require more frequent assessments of program adequacy in the face of climate change. Whenever a monitoring program is judged to be inadequate, changes should then be implemented to ensure that these programs retain their utility to management. These various responses to climate change represent natural components of adaptive management. In particular, climate change will lead to increased frequency and importance of the double-loop phase of adaptive management.

CASE STUDY: WATERFOWL HARVEST MANAGEMENT

Our discussion of climate change, its relevance to management programs, and possible responses to it within these programs has been general. Here, we consider a specific ongoing management program and discuss possible modifications to this program that could result from efforts to adapt it to climate change. Waterfowl management in North America has a rich history characterized by over a century of cooperation, ground-breaking legislation, and scientific advancement. In 1995, the United States Fish and Wildlife Service and Flyway Councils reached another benchmark in the evolution of the profession with the initial implementation of adaptive harvest management (AHM; see Williams and Johnson 1995, Nichols 2000). The AHM process was grounded in the fundamental principles of adaptive resource management and represented one of the first formal applications of these general ideas to a specific management problem. The AHM process is notable in several ways. Importantly, it established clear distinctions between policy and technical aspects of regulatory decisions, which helped to structure and more appropriately focus ongoing debate over regulations. Adaptive harvest management, despite its highly technical underpinnings, also improved transparency of the regulatory decision-making process.

Adaptive harvest management has gone through several phases of development common to all adaptive decision-making processes: the setup, iterative, and double-loop phases. The setup phase involved construction of the adaptive decision framework including development and specification of 1) explicit and measurable objectives (e.g., focusing on accumulated harvest over a long time horizon, see Johnson et al. 1997), 2) management actions or alternatives available to the decision maker (i.e., hunting regulations packages, Johnson et al. 1997), 3) a suite of competing system models that codify alternative hypotheses about the way the managed system works and responds to management actions (e.g., hypotheses about population responses to harvest; see Johnson et al. 1997), 4) monitoring programs that permit estimation of critical state variables and vital rates and testing of predictions of the competing models (e.g., see Nichols et al. 1995), and 5) optimization methods to help make the best decision based on current system state and relative beliefs in the alternative models (e.g., Williams 1989, 1996).

The iterative or operational phase of AHM has been in place since 1995. The annual AHM decision process unfolds as follows. Results of annual monitoring of waterfowl population status and habitat conditions are used in conjunction with competing models to make alternative predictions about the extent to which the available management actions would achieve stated management objectives. Predictions of the alternative models are weighted by managers' relative confidence in each model (model weights or credibility measures), and an optimal annual regulatory decision is made. This optimal decision is based on the current status of the population and habitats, as well as on the various models and their respective weights. Each competing model makes a prediction about population status the following year based on the management action that is taken. Then, in the following year, monitoring programs again collect targeted information on the status of populations (as well as on habitat status and harvest rates). These new data are compared to the predictions about status made by the competing system models the preceding year, and the weights of the models are adjusted according to how well or poorly they predicted the current year results. These updated model weights, together with the new monitoring data describing the current state of the system, are used to begin another iteration of the adaptive decision cycle.

Concurrent with ongoing implementation of AHM, the waterfowl management community has entered the third phase of development, the double-loop phase (e.g., see Runge et al. 2006). In this phase, policy makers and technicians are circling back and reconsidering management objectives and alternatives, the AHM modeling framework, and monitoring programs. Are the policy elements of the strategy (i.e., objectives and regulatory options) still relevant? Do they capture and appropriately weight fundamental objectives? Do system models still adequately describe the range of critical uncertainties confronting policy makers? Do monitoring programs still permit inference about relevant parameters at appropriate scale and resolution? If additional hypotheses and competing system models are incorporated, can current monitoring programs help discriminate among them? Uncertainty over the effects of climate change on waterfowl and their habitats is factored into renewed deliberations concerning all the elements of AHM: objectives and alternatives, models, and monitoring programs.

Though the future impacts of climate change on migratory birds in North America are largely unknown, there are several reasonable hypotheses, including predicted changes in spring phenology and mismatches in the timing of resource availability, range and distributional shifts, habitat changes, and changes in exposure to disease and parasites. As part of the process of double-loop learning, these hypotheses should be included in discussions about all of the elements of the AHM process. In fact a likely initial change in the conduct of AHM in response to climate change will be an increase in the frequency with which AHM elements are revisited in the double-loop phase.

With respect to AHM objectives, recent discussions have focused on population sizes that are not only desirable, but also reasonable with respect to concepts of carrying capacity and available habitat. These discussions emerged from the recognition that management efforts directed at harvest and habitat have been treated separately in the past. A far more reasonable approach is to establish a coherent framework to treat harvest and habitat management objectives simultaneously or at least in a manner that links objectives for these 2 kinds of management actions (Runge et al. 2006). Predicted changes in patterns of precipitation should figure heavily into these discussions, leading to the possibility of dynamic objectives. The intent with such objectives would be to acknowledge changes in waterfowl reproductive rates and population size that might be expected to accompany major changes in precipitation and wetland habitat in key breeding areas. Although population objectives that are changed periodically are not commonplace in wildlife management, they will likely receive increased consideration in the face of rapid climate change.

Available management actions will likely be revisited as well during double-loop considerations of potential responses to climate change. For example, dramatic increases in abundance of lesser snow geese (*Chen caerulescens*) and other light geese have been attributed to recent changes in wintering ground habitat associated with farming practices. The increased goose abundance has led to special hunting seasons designed to control numbers (e.g., Alisauskas et al., in press). It is possible that climate change could produce similar dramatic changes in waterfowl numbers that would prompt a reconsideration of available management actions. It is also possible that aspects of climate change (e.g., precipitation and temperature) will produce widespread habitat changes that may provide new opportunities and needs for habitat management.

The models that predict system responses to management actions will almost certainly require modification and revision to deal with climate change. As we discussed, the number of wetlands in key breeding areas of North America is an important predictor of mid-continent mallard reproductive rate. Wetland numbers in a future year are predicted as functions of wetland numbers the current year, assuming a constant relationship (stationary process) based on autoregressive analyses of historic data. Because of predicted changes in patterns of precipitation, we anticipate the development of AHM models that incorporate predicted changes in pond distributions over time, rather than characterizing pond numbers with a static distribution. In the AHM models for mid-continent mallard populations, wetlands on breeding grounds are already incorporated as a state variable, so modification of models would involve modeling dynamics of this variable as nonstationary.

The latitudinal distribution of breeding and wintering waterfowl has been found to be an important determinant of survival, harvest, and reproductive rate for both ducks and geese and constitutes another feature of waterfowl biology that is likely to evolve with climate change. Climate change will thus likely necessitate development of models that include not only responses to management actions (e.g., hunting regulations), but also temporal changes in distributions of baseline vital rates as expected to accompany geographic shifts. It is conceivable that changes in predator communities affecting waterfowl may occur as a function of climate change, also leading to changes in waterfowl vital rates. Specific predictions about climate change effects on birds and associated predator communities can be made by simultaneously considering predictions of alternative future climate states from global climate models and down-scaled regional climate models along with alternative predictions of the hypotheses we mentioned previously. New or revised AHM system models will have to incorporate the uncertainty associated with alternative future climatic states, and special attention will need to be focused on framing alternative models that contrast sharply in their management implications.

Similarly, waterfowl population and habitat monitoring programs are currently being reviewed to determine if they continue to permit inference about relevant state variables and vital rates needed to inform decisions and learn. This review addresses several important questions relevant to climate change. Are population changes that are observed real or artifacts of birds redistributing outside traditional survey boundaries or adjusting timing of migration? Will current monitoring programs allow for discrimination among a revised set of system models that incorporate uncertainty related to climate change effects? If not, can they be revised to do so, or are new monitoring programs required? Predicted changes in distribution patterns of focal populations may necessitate expansion of survey programs (e.g., aerial surveys) into locations that currently receive little or no survey effort. For example, we can envision the possibility of new strata established near range peripheries and sampled at low intensity initially, with the possibility of evolving to higher-intensity sampling if substantial numbers of birds are encountered. Adaptive sampling (Thompson and Seber 1996) might provide a useful sampling design within such strata for species that aggregate in space. Some species may exhibit contractions in southern portions of their ranges, again motivating changes in survey strata and boundaries.

Some existing monitoring programs (e.g., banding programs) focus on vital rates (e.g., Martin et al. 1979), and changes to these programs should also be considered with respect to climate change. For example, evidence exists within multiple North American duck species that reproductive rates vary substantially as a function of breeding ground latitude (e.g., Smith 1970, Calverley and Boag 1977). Survival rates of North American ducks have also been shown to vary as functions of breeding ground latitude and migration distance (e.g., Bowers and Martin 1975, Nichols and Johnson 1990, Hestbeck et al. 1992). Changing distribution patterns of birds induced by climate change could lead to substantive changes in vital rates. Adequate banded sample sizes at multiple latitudes and locations will be useful in providing inference about changes in survival rates associated with changing distribution patterns of birds. Information from such monitoring programs will be needed to estimate changes in baseline vital rates required by management models. In all cases, the design or redesign of monitoring programs should be dictated by the decision-making context and associated uncertainties, including climate change.

Optimization algorithms used to determine optimal harvest decisions may require modification to deal appropriately with climate change. The algorithm currently used, stochastic dynamic programming (SDP; Bellman 1957, Lubow 1995), considers not only the current time step (anticipating results of imposing a set of regulations on this year's harvest and on next year's population size), but also time steps into a specified, or frequently indefinite, future. The system is expected to exhibit dynamics in the future, but those dynamics are governed by a model with parameters that remain constant over time (stationarity). The optimizations may need to be modified to explicitly incorporate parameters that evolve over time themselves. This proactive approach to decision-making will likely produce decisions that depend not only on system state, but also on time. As we noted, an alternative approach is to focus optimization on a finite (likely short) time horizon (e.g., 5–10 yr into the future) with the expectation that system change will necessitate new models and optimization efforts during the next phase of double-loop learning. Such an approach requires careful specification of the terminal values of key state variables in each optimization, as these values will constitute the initial conditions for the next set of management decisions. The frequent development of new models also requires monitoring that is especially focused on the latter portion of each time horizon, as conditions in these periods are likely to provide a better basis for new models, when systems continually evolve.

CHALLENGES

We anticipate several challenges to existing adaptive management programs that will result from the added uncertainty of climate change. Some of these challenges will be more technical, whereas others will be more institutional or political.

Institutional and Political Challenges

Institutional and political challenges relate primarily to the first 2 elements of the structured decision process, namely the specification of objectives and management actions or alternatives. Although climate change certainly exacerbates the institutional challenges faced by natural resource managers, many of these challenges are not fundamentally new and, in fact, have been recognized and debated by the ecological, economic, political, and legal communities for decades.

Objectives.– In some cases, decision problems are straightforward from an institutional or political perspective, especially when the number of stakeholders is few (or at least when stakeholders hold similar perspectives about the desirability of different management outcomes) and the number of decision-makers is limited. Such is the case in waterfowl harvest management where, despite the many stakeholders, most would support, or at least be ambivalent to, objectives to establish hunting regulations commensurate with the potential of populations to sustain harvest. In addition, decision-making authority is clear, legally established, and vested (in the U.S.), ultimately, in one individual.

The scope and scale of many other environmental management problems and decisions are not so constrained. Successfully addressing them will require coordinated action across large ecosystems in pursuit of common objectives. Objective-setting becomes considerably more challenging in an institutional or political context that involves numerous stakeholders with divergent interests and agendas, as well as numerous decision-makers possibly including private landowners, businesses, and local, state, and federal government agencies. Such is the case with many decision problems expected to accompany climate change. To adequately address such natural resource conservation problems, the process of objective-setting must be viewed within a broader societal context that also includes social, economic, and political considerations. The need to better incorporate this social context in the management process has been recognized as a fundamental challenge in applying structured or adaptive decision processes to ecosystem management for decades and exists irrespective of climate change (e.g., United Nations World Commission on Environment and Development 1987, Lee 1993:11, Gunderson et al. 1995, McLain and Lee 1996, Walters 1997, Cortner et al. 1998, Williams 2003). In general, appropriate forums for public–private dialogue in objective-setting are poorly developed, and past models for public participation and the integration of societal values in governmental policy formulation are likely outmoded (Cortner et al. 1998). Today, there are many tools and techniques that can be used to facilitate the informed dialogue needed to identify and balance fundamental tradeoffs among competing interests and objectives for natural resource management (e.g., Keeney and Raiffa 1993). However, important stakeholders must have a seat at the table for these tools to be effective. Climate change will require us to deal more effectively with objective-setting.

In addition to challenges in improving public participation, fundamental changes to management institutions may be necessary to facilitate more comprehensive and integrated objective-setting for natural resources management. Government agencies have distinct jurisdictions and mandates that may overlap or even directly conflict with one another. Often, jurisdictions and mandates are poorly aligned with ecosystem or socioeconomic processes, and no mechanism or structure exists to foster collaboration. A recent Government Accountability Office (GAO) report (2009) on improving natural resources decision-making for climate change adaptation found that a lack of clearly articulated roles and responsibilities at the federal level has led to power struggles that undermine needed collaboration. Agency roles and responsibilities can only be defined in the context of shared and explicit objectives. Institutional structures based on management philosophies of the past may need adjustment to meet increasingly complex environmental problems. Gunderson et al. (1995) suggested the need for a crisis or catalyst to change the way society addresses multiple, competing objectives. We are hopeful that the present attention directed toward climate change will catalyze adjustments in institutional structures and processes that presently inhibit open and ongoing public participation as well as collaborative, inter-jurisdictional response to environmental challenges (including climate change).

A specific challenge associated with objective-setting for natural resource management, to which climate change will draw increased attention, is the issue of nonstationarity of ecological and socioeconomic systems (GAO 2009). In the past, many conservation and management objectives have been established on the assumption of long-term system stationarity; that is, while short-term fluctuations in system dynamics exist, these fluctuations occur around some long-term central tendency. In addition, our knowledge of both central tendencies and variation is informed by past conditions. Climate change is expected to result in the breaching of ecological thresholds resulting in directional change in the dynamics of ecological systems (Climate Change Science Program [CCSP] 2009). As ecological systems change, concomitant shifts in socioeconomic systems can be expected.

In the face of such change, objectives established under the assumption of stationarity may be unattainable. In some cases, management objectives that scale to, or accommodate, prevailing climatic (and related ecological and socioeconomic) constraints will be needed (Williams 2003). For example, reduced northern pintail (*Anas acuta*) numbers over the last 3 decades have been attributed by many to decreased reproductive rates associated with widespread changes in suitable breeding ground habitat. Reduced population sizes have led to substantial changes in stakeholder expectations for potential harvest. Population sizes and growth potential of several North American duck species are highly influenced by the availability and condition of ephemeral wetlands that occur in the northern plains. Should climate change cause widespread drying of these wetlands, and the productive capacity of this landscape is not recouped in other areas affected by climate change, it is likely that no amount of conservation investment will enable attainment of duck population objectives developed based on historic conditions under an assumption of climate stationarity. Duck population objectives that scale to climatic realities could be developed and used to appropriately allocate conservation resources.

Scalable objectives would certainly meet resistance because they could be perceived as defeatist or noncommittal, allowing resource managers to sidestep accountability for failure to achieve objectives. Mechanisms to improve public participation in objective-setting and decision-making could reduce suspicions by providing an open, well-documented process that considers multiple, competing interests, describes a rationale for balancing tradeoffs, and acknowledges the reality of limited societal resources to address climate change impacts.

Actions.– Adaptive management requires a defined set of available management actions from which to select at each decision step (Walters 1986, Nichols et al. 1995, Williams et al. 2007). These actions should have some expected or hypothesized effect on the attainment of management objectives and thus must be focused at relevant taxonomic, spatial, and temporal scales. Collections of actions, and rules that dictate the applicability of specific actions, define a management policy or strategy. As a framework for learning from management actions, adaptive management, particularly for large and complex systems, often requires a long-term commitment to management strategies. It also requires institutional flexibility to adjust management actions (and objectives) on the basis of new information.

Institutional commitment and flexibility have challenged the application of adaptive management principles to resource conservation in the past (Lee 1993:80–86, Doremus 2001, Garmestani et al. 2009). These challenges will be increased by the kind of system change anticipated as a result of climate change. Governmental budgetary and political cycles are frequently shorter, often considerably shorter, than the lifecycle of adaptive decision processes. Indeed, adaptive management, particularly for large and complex systems, is accurately thought of as a process for ongoing and long-term decision-making, where the process may be more relevant than some fixed outcome. This emphasis on the decision-making process is particularly important in the face of climate change and the shifting ecological and socioeconomic contexts it portends. Short-term budgetary and political cycles are not particularly conducive to large-scale and long-term approaches to management, as in the case of more actively adaptive strategies, because the costs of learning, although beneficial over a long time horizon, may come at the price of short-term benefits derived from the management activity. For large and complex systems, such tradeoffs may be intergenerational, that is the costs are borne by today's resource users and managers, with an expectation that future resource users and managers will benefit (Walters 1997). Strong institutional leadership is needed to maintain commitment to long-term adaptive decision processes in the face of short-term shifts in budgetary and political winds. However, institutional leadership, too, is ephemeral. In the end, maintaining institutional support for adaptive management will likely require a fundamental philosophical shift within natural resource management agencies and organizations from a perception that structured decision-making principles and adaptive management are applicable only in narrow contexts that focus on evaluation of a specific management treatment to viewing them as a standard process for decision-making and conducting business.

Institutional flexibility is also essential for successful implementation of adaptive decision processes. For many governmental agencies, existing regulations and environmental legislation greatly restrict agency flexibility. In particular, many of today's environmental regulatory agencies are not well suited to integrating new scientific knowledge into resource management decisions or recalibrating policy and regulations in light of new information (Doremus 2001, Garmestani et al. 2009). The rigidity and certainty of environmental law and associated agency regulations that were useful in the past in addressing straightforward environmental problems (e.g., point-source pollution) now limit agencies' abilities to apply adaptive principles in addressing complex problems involving many stakeholders and jurisdictions as well as shifting ecological and socioeconomic systems (Ruhl 1999, Doremus 2001, Garmestani et al. 2009).

The challenge to today's institutions is to combine flexibility to adjust policies to new information with accountability to the regulated public (Doremus 2001). Stated another way, regulatory rules and agency decisions must be clear to the public, but at the same time agencies must have the ability to adjust to evolving understanding and shifting ecological and socioeconomic contexts. Adjustments to environmental legal frameworks to achieve such balance are the subject of ongoing debate in the United States. Interestingly, the principles of adaptive management that challenge today's legal structures may, in fact, offer a solution to the problem of balance between institutional flexibility and accountability. We suggest that broader adoption of adaptive principles in natural resource decision-making could aid in achieving such balance by shifting scrutiny away from individual regulatory decisions and on to transparent and explicit adaptive decision frameworks that are collaboratively developed up-front with input from key stakeholders. Under this conceptual approach the negotiated adaptive decision framework offers explicit decision rules that are transparent to decision makers and stakeholders, including rules about how new information will enter into the decision-making process in the future. This largely mirrors the process used by the United States Fish and Wildlife Service in promulgating annual waterfowl hunting regulations and is consistent with guidance for implementation of adaptive management recently offered to United States Department of the Interior bureaus (Williams et al. 2007).

Technical Challenges

Technical challenges tend to concern the final 3 elements listed above for structured decision processes: models, monitoring, and optimization.

Modeling.– In our discussion of modeling, we focused on the challenges imposed by nonstationarity of climatic variables that are important drivers of system dynamics. We noted that there exist at least 2 approaches to dealing with this issue in modeling, with the selected approach depending on the degrees to which important climatic drivers can be identified and modeled.

Climate variables that are recognized to be important to the managed system and that can be modeled, can be added to system models as additional state variables. This addition increases the number of state variables to consider but, for projection purposes, this increased dimension does not present a real problem. The more important challenge will be deciding how to model the dynamics of such state variables into the future. Such modeling will depend on either recent historic data (assuming that change in the climate variable has been occurring) or climatic projections based on variables driving climate change. In both cases the projections will often involve values of climate variables that extend beyond historic experience for the location(s) being managed. Such modeling outside the realm of historic experience is characterized by great uncertainty. One response to this uncertainty might be to include structural uncertainty associated with the climatic variable itself in the form of multiple climate models. But this additional structural uncertainty has the potential to substantially increase the number of overall models considered.

For example, the AHM program for mid-continent mallards includes 4 models that reflect different hypotheses about mallard population responses to hunting. We noted that pond dynamics are modeled as a stationary Markov process based on the assumption of stationary precipitation dynamics. One approach to climate change would be to model pond numbers in year $t + 1$ as a function of pond numbers in year t and precipitation occurring between t and $t + 1$. Precipitation itself could then be incorporated as an additional state variable. Assume there are 2 competing models about how precipitation will change over time. Because pond numbers (and thus precipitation) are important in all 4 mallard models, the 2 precipitation models should then be considered with each of the mallard population models, effectively increasing the model set from 4 to 8. On the other hand, it may be that uncertainty associated with the new precipitation models is so important (in the sense of leading to dramatically different predictions about duck populations) that it may be reasonable to effectively ignore other sources of uncertainty. For example, we might eliminate competing models corresponding to management effects that are relatively minor with respect to projected harvest and abundance. The key to such modeling decisions will be to focus on the uncertainty that is most relevant to the management decision, a recommendation that applies to all informed management (e.g., Williams et al. 2002).

The other way to deal with nonstationarity applies when we do not recognize the importance of a climatic variable that actually drives system dynamics, or else when we do recognize its importance but have no idea how to model its changes over time. In both cases, the system is changing over time in a way that cannot be predicted. As suggested above, perhaps the best approach in this case is to be especially vigilant about model adequacy, imposing double-loop learning when evidence emerges that the predictive abilities of the models are declining. Under this admittedly reactive and ad hoc approach, managers would proceed for relatively short periods of time with one model set. Increasing evidence of reduced predictive abilities would prompt managers to revisit the model set, making modifications that seem appropriate based on recent system dynamics. This modified model set would then be used until predictive abilities declined, at which time the set would be again revisited and perhaps revised. This approach is based on an admission that we either cannot identify the important drivers of system dynamics, or that we can perhaps identify them but have no idea about how to model their dynamics. In the face of such ignorance, frequent development of new models may be the best course of action.

Perhaps the most substantial technical challenge associated with this latter approach is development of the new model set. Typically, managers rely heavily on existing data when developing models for use in natural resource management. Model set development usually begins with a priori hypotheses, and corresponding models are then fit to actual data sets. In the case of system change, models are hopefully still developed based on a priori hypotheses, but there will be little historical data for use in estimating model parameters. In the case of system change, model development will likely rely heavily on very recent data and on the nature (e.g., magnitudes and signs) of deviations of these data from model-based predictions, the very deviations that led to recognition of the need for a new model set. Beyond this emphasis on use of recent data, we anticipate a greater use of deductive reasoning and a decreased ability to use historical data when developing new models to deal with system change.

Monitoring.– Our discussions of monitoring and partial observability emphasized 2 important sources of variation in most animal monitoring programs: geographic variation and detection probability (Yoccoz et al. 2001, Nichols and Williams 2006). Most animal populations are distributed over areas sufficiently large as to require sampling of space, rather than surveys that cover every square kilometer of the entire range. Sampling designs for populations inhabiting large areas frequently involve stratification by habitat as a means of obtaining efficient estimates (e.g., Smith 1995, Williams et al. 2002). For historical surveys of animal populations and communities, stratum boundaries have usually changed little over the time of survey conduct. However, climate change is bringing about substantive changes in habitats, suggesting that frequent restratification will be warranted. Restratification will have to be based on information, suggesting that data on habitat variables once viewed as constants (and hence ignored in animal surveys) should now be regularly collected as part of the animal survey, at least periodically. At a minimum, vigilance about adequacy of stratification will be required.

In addition to stratification within existing survey boundaries, climate change introduces the prospect of range extension beyond current survey boundaries. Many animal monitoring programs were established in attempts to cover entire species ranges, whereas climate change has led to range contractions in some areas and expansions in others. Information about range contractions comes directly from animal monitoring programs, as some areas see decreased use and perhaps local extinction over time. Such areas can then be dropped from future surveys, if recolonization is not anticipated. Range expansion to areas not included in current survey boundaries is problematic, as the current survey does not necessarily provide information about such shifts. Sometimes, anecdotal information about range shifts may come from biologists or other citizens living in areas outside former range boundaries to which populations have expanded. However, reliance on such anecdotal information may not be desirable. An alternative approach would be to expand current survey boundaries to encompass neighboring areas to which population expansion is thought to be likely. Survey methods for these neighboring areas might be completely different from those within the main survey area (e.g., use of occupancy rather than abundance as a state variable; MacKenzie et al. 2002, 2006), as they would be directed at detection of range shifts. Development of such extended monitoring programs would represent a technical challenge, as there has been little historic interest in, or need of, such programs.

Detectability is the other primary source of variation in data emerging from animal population and community monitoring programs. Animal monitoring programs have traditionally used one of 2 approaches for dealing with variation in detection probabilities: standardization of data collection methods and direct inference about detection probability parameters. Standardization represents an attempt to minimize variation in detection probabilities over time and space such that counts from different times and locations are comparable in the sense that they represent the same proportion of the true numbers of animals at each time and place. However, regardless of the exact methods used for counting animals, sources of variation in detection probabilities typically include large numbers of factors beyond counting methods (e.g., Williams et al. 2002). For example, detection probabilities frequently vary as functions of habitat and environmental variables, quantities expected to vary systematically with climate change. We noted above that surveys based on counts of breeding animals (e.g., vocalizations of breeding male songbirds) at specific sets of dates within a year may be affected by changes in phenology. Specifically, changes in avian breeding phenology could lead to changes in the fraction of birds calling during a particular range of survey dates, as the dates might represent periods that are progressively more advanced with respect to breeding seasons (e.g., Crick and Sparks 1999).

The preferred way of dealing with such issues, in our opinion, is to not rely on standardization as a means of dealing with detectability, but to instead use the alternative approach of designing the survey to obtain data permitting direct inference about detection probability. Then one need not worry about identifying all of the sources of variation in detection probabilities and specifying how these sources vary in response to climate change. Although we base our recommendation on the belief that reasonable approaches can be found to deal with detection issues in most animal monitoring programs, there are still some technical challenges associated with detectability (e.g., Nichols et al. 2008) that must be addressed by monitoring programs to insure their utility in the face of climate change.

Optimization.– We alluded to potential problems in computing optimal solutions to decision problems in our discussion of the case study. We noted that SDP is currently the optimization algorithm of choice for state-dependent recurrent decisions. It is insufficient to deal simply with optimization for single time steps, because current actions affect future states, which in turn influence future management options and associated utilities. Virtually all of our experience with SDP is with stochastic processes that can be viewed as stationary. Thus system dynamics and responses to management are modeled as characterized by the same distributions through time. When we can identify important environmental drivers that are themselves evolving, we have already suggested that they be included in models as additional state variables to be modeled themselves. We have little experience with use of such models for nonstationary processes with

SDP. At a minimum, optimal solutions will likely now be time-dependent rather than stationary. Also, any addition of state variables to an optimization problem increases dimensionality, and inability to handle problems of even moderate dimension is one of the primary factors limiting use of SDP. In addition to these issues, other technical problems may arise in the face of nonstationarity. Thus, formal approaches to optimization of nonstationary systems over moderate–long time horizons present an immediate technical challenge, although ongoing work by computer scientists on alternative approaches (e.g., reinforcement learning, genetic algorithms) may soon provide satisfactory solutions.

Modification of algorithms for optimization may be appropriate (assuming that technical challenges can be overcome) for situations in which key environmental drivers can be identified and models developed for their evolution over time. This approach is not applicable to the alternative situation we discussed above under the Modeling Section, in which key environmental drivers cannot even be identified or else can be identified but not modeled. As we noted above in the case study, an alternative approach is to focus optimization on a short time horizon (e.g., 5–10 yr into the future), with the expectation that system change will necessitate development of new models during the next phase of double-loop learning. Optimization over such short time horizons is less intensive, computationally, but requires additional considerations that do pose technical challenges. We have already noted that development of new models based on limited historical data presents a difficult challenge. Terminal values of state variables for the intervals of optimization assume special importance in these short-term optimization problems, as these values will become the initial conditions for the next set of management decisions. Managers require optimization results that are robust in the sense of leaving the system in a state that is not vulnerable to unanticipated changes in either environmental variables or, perhaps more importantly, system dynamics and responses to management. Given some ability to predict or anticipate at least the general nature of new system models, we might consider use of simulation-based approaches to develop management strategies that are good (not necessarily optimal) over moderate time horizons that represent multiple sequences of these short-term horizons. However, in the complete absence of any ability to predict the nature of new system models, it is difficult to imagine how to go beyond the simple approach of short-term optimization for robust values of terminal states. Development of reasonable approaches to optimization will thus present serious technical challenges that must be addressed.

If challenges to the 2 described approaches to optimization prove too difficult to overcome, then we may need to consider other approaches for identifying wise management decisions. Info-gap decision theory (Ben Haim 2006) seeks to optimize with respect to robustness to failure under extreme uncertainty and may prove useful for natural resource management under climate change. It may also be appropriate to abandon the idea of global optimization in some cases and simply seek good (not necessarily optimal) solutions by exploring limited sets of alternative approaches to management via computer simulation. For example, different rules of thumb for selecting management actions, or even different sequences of actions, can be simulated under different climate scenarios. Approaches that are good with respect to specified criteria (e.g., returns, robustness to failure) could then be selected for use.

CONCLUSION

Responses of managed natural resource systems to climate change are characterized by substantial uncertainty, and managers are rightly concerned about how to deal with this uncertainty. This concern has led to pleas for innovative solutions to the perceived new challenges posed by climate change. Our response is not to downplay these concerns, as we take them seriously as well. But rather than calling for new approaches to management, we emphasize that uncertainty has always characterized most problems in natural resource management and that approaches have been developed for confronting uncertainty when making decisions. Specifically, adaptive resource management is becoming more widely used for natural resources precisely because it does deal with uncertainty and its reduction over time. Rather than view climate change as a source of uncertainty that requires a new approach to management, we believe that adaptive management provides a good framework for dealing with climate change as well as with other sources of uncertainty.

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