Monitoring in the Context of Structured Decision-Making and Adaptive Management

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ABSTRACT In a natural resource management setting, monitoring is a crucial component of an informed process for making decisions, and monitoring design should be driven by the decision context and associated uncertainties. Monitoring itself can play ≥3 roles. First, it is important for state-dependent decision-making, as when managers need to know the system state before deciding on the appropriate course of action during the ensuing management cycle. Second, monitoring is critical for evaluating the effectiveness of management actions relative to objectives. Third, in an adaptive management setting, monitoring provides the feedback loop for learning about the system; learning is sought not for its own sake but primarily to better achieve management objectives. In this case, monitoring should be designed to reduce the critical uncertainties in models of the managed system. The United States Geological Survey and United States Fish and Wildlife Service are conducting a large-scale management experiment on 23 National Wildlife Refuges across the Northeast and Midwest Regions. The primary management objective is to provide habitat for migratory waterbirds, particularly during migration, using water-level manipulations in managed wetlands. Key uncertainties are related to the potential trade-offs created by management for a specific waterbird guild (e.g., migratory shorebirds) and the response of waterbirds, plant communities, and invertebrates to specific experimental hydroperiods. We reviewed the monitoring program associated with this study, and the ways that specific observations fill ≥1 of the roles identified above. We used observations from our monitoring to improve state-dependent decisions to control undesired plants, to evaluate management performance relative to shallow-water habitat objectives, and to evaluate potential trade-offs between waterfowl and shorebird habitat management. With limited staff and budgets, management agencies need efficient monitoring programs that are used for decision-making, not comprehensive studies that elucidate all manner of ecological relationships. (JOURNAL OF WILDLIFE MANAGEMENT 72(8):1683–1692; 2008)

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Wildlife management is an exercise in decision-making—choosing actions that are expected to best achieve management objectives. Framing any wildlife management question in terms of a formal decision process is a powerful strategy because it allows the question to be deconstructed and examined using the tools of decision analysis (Raiffa 1968, Clemen 1996). Many wildlife management decisions are difficult because the objectives are contentious, the possible management actions are limited, and the response of the resource is uncertain; yet, making good decisions requires integrating all these elements. Structured decision-making provides methods for first analyzing, then integrating, these components.

Monitoring plays a central role in wildlife management because the systems we manage are dynamic and variable, and often we do not understand how they will respond to our decisions and actions. Williams (1997, 2001) described several sources of uncertainty that affect natural resource decisions. First, environmental variation in space and time often drives resource systems in ways that may or may not be consistent with management prescriptions. Second, considerable uncertainty often exists about underlying biological mechanisms responsible for observed patterns (i.e., structural uncertainty; Williams 1997, 2001). Third, many system variables are not measured directly (i.e., partial system observability), and fourth, outcomes of management actions often deviate in degree and spatial extent from management prescriptions (i.e., partial management control; Williams 1997, 2001). By integrating monitoring into decision-making, adaptive management explicitly addresses these sources of uncertainty and allows decision-makers to simultaneously achieve management objectives and generate new knowledge about how the system responds to management (Williams and Johnson 1995, Lancia et al. 1996, Kendall 2001).

For applied problems in wildlife management, monitoring is not an end in itself but derives its purpose and value from the decision context (Nichols and Williams 2006), specifically from the nature of the decision, the management objectives, the uncertainties about how the system responds to management, and the potential for monitoring information to improve future outcomes. Without this context, monitoring can easily become either inefficient (using staff and fiscal resources that could be directed elsewhere) or ineffective because monitoring cannot logically inform the decision-making process (Gibbs et al. 1999). Clearly, for monitoring to inform wildlife management decisions, there must be a strong connection between the monitoring design and decision structure. Our goal was to explore the specific roles of monitoring in the context of adaptive management and other forms of structured decision-making.

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STRUCTURED DECISIONS, ADAPTIVE MANAGEMENT, AND MONITORING

Structured decision-making embodies a large set of tools for analyzing decisions, but the general approach involves decomposing a decision into basic elements, developing those elements, and then finding the solution in the integration of those elements. Adaptive management is a special case of structured decision-making, applicable when the decision is iterated over time or space and there are competing hypotheses about how the system operates. The iteration and competing hypotheses result in an opportunity for learning (through monitoring) and making use of what is learned to improve decisions made at subsequent times or other sites (Williams et al. 2007). Nichols and Williams (2006) contrast targeted monitoring, which is integrated in conservation and management decisions, with omnibus surveillance monitoring, which lacks a priori hypotheses and models. Below, we first discuss structured decision-making, then adaptive management, and finally the roles of monitoring in each.

Elements of a Structured Decision

A decision-analytic framework helps decision-makers manage uncertainty and make use of as much available information as possible (Clemen 1996, Hammond et al. 1999). Decision analysis begins with identification of 3 basic elements: 1) objectives, 2) a set of potential actions from which to choose, and 3) some expectation of consequences related to each potential action, in terms of the objectives. Immediately, this deconstruction identifies distinct roles for stakeholders and scientists: stakeholders articulate the objectives and their relative importance, scientists make predictions about the consequences of various actions, and both groups play a role in identifying potential actions that are both possible and agreeable.

A clear statement of objectives is essential. Objectives are specific outcomes or performance measures that guide decision-making and are used to evaluate success of actions (Keeney 1992, Clemen 1996). Objectives are often explicitly stated in terms of maximizing (or minimizing) one or more quantitative measures of performance (Peterman and Peters 1999), although $\geq$1 branch of decision theory emphasizes the robustness of satisfactory performance rather than the pursuit of optimal performance (Ben-Haim 2001). In most decision problems, 2 types of objectives can be identified: fundamental and means objectives (Keeney 1992). Fundamental objectives are the results decision-makers care about most; means objectives are steps sufficient (or believed sufficient) to help accomplish fundamental objectives. In a natural resources setting, examples of fundamental objectives include maximize abundance of species A or maximize species richness on management unit X. Means objectives are often related to improving habitat quality or quantity for species of management interest. Separating fundamental and means objectives during the setup phase helps identify the core values of the stakeholders. Fundamental objectives can usually be identified and refined by repeatedly asking stakeholders, in reference to a particular objective, why is this important? (Clemen 1996, Hammond et al. 1999).

The essence of a decision is the choice of one action from a set of alternative actions. Developing the list of potential actions is often difficult, however. In some cases, effective actions do not exist, so the challenge is to engineer a novel action. For example, the solution to a number of beaver management problems required the invention of the beaver pipe (Leighton and Lee 1952). In other cases, effective actions exist but may be unacceptable alternatives to some stakeholders (e.g., certain types of lethal control for beaver management). Other considerations in developing a list of alternative actions include the number of options to include, the degree of difference between them, and legal and regulatory constraints on them (Williams et al. 2007). Thus, articulating a set of alternative actions requires both scientific and stakeholder input and consideration of potential efficacy and political support. One of the hallmarks of a structured decision, however, is that the potential actions are outlined explicitly in advance.

The third required element for a structured decision is a set of statements about likely outcomes of each potential action, stated in terms that can be linked to the objectives. That is, a model is needed that describes how we think the system responds to management actions. In some simple cases, this model might take the form of a decision tree, combining known information, probabilities for uncertain events, and consequences of outcomes for each alternative action (Raiffa 1968, Clemen 1996, Peterman and Peters 1999). In other cases, a more complex population model might be required to describe the demographic outcomes expected as a consequence of each potential action, with the various types of uncertainty incorporated explicitly into the predictions (Starfield and Bleloch 1986, Kendall 2001). Note that even qualitative and intuitive expectations constitute a model, in that they link the potential actions with expected outcomes and serve as a prediction for how the system will respond to management. Therefore modeling is not an option but is inherent to any informed decision-making process. The advantage of explicit, quantitative models is that they are objective, transparent, and amenable to analysis.

Once a decision-maker articulates the objectives, alternative actions, and a model, the analysis proceeds through some form of optimization (i.e., finding the action that best achieves the objectives given the expected responses as captured in the model). There is a wide variety of techniques for analysis, with the appropriate method depending on the nature of the decision, the form of the objectives, and the capability of the model (Clemen 1996, Hammond et al. 1999, Williams et al. 2002).

Dynamic Decision Analysis and Adaptive Management

Whereas the basic elements of a structured decision apply to all decision problems, even simple one-time decisions, dynamic decision analyses pertain to a subset of decision problems in which the decision is iterated over time, which provides an opportunity to apply learning from earlier decisions to improve later decisions (Puterman 1994, Williams et al. 2007). Uncertainty about the outcome of a chosen action (e.g., due to environmental variation or partial controllability) is acknowledged, and therefore a state (e.g., new population level or plant composition) different than the one expected might result. The next decision depends on the realized new state, not the expected new state. A monitoring program is crucial under a dynamic decision process not only to determine the realized new state but also to evaluate the outcome of the last decision with respect to the objectives.

Adaptive management constitutes a dynamic decision analysis where instead of one predictive model of the system, there are multiple models derived from competing hypotheses about how management actions affect the system of interest. Each predictive model contains explicit statements about what is known and unknown and is used to derive an expected response to any management action applied under a given set of conditions. Each model is given a model weight or degree of belief (i.e., the relative likelihood of each alternative hypothesis about the state of nature). All of the competing models influence the selection of the optimal decision through their assigned weights. In this way, adaptive management is about taking action in the face of uncertainty, not waiting until there is enough information to take action with perfect knowledge. Managers and other decision-makers are able to simultaneously achieve management objectives and work toward a greater understanding of how the system functions and responds to management (Walters 1986, Williams et al. 2007).

Monitoring provides the feedback loop to complete the cycle of planning, implementation, and evaluation. Observations from the monitoring program are periodically compared with predictions of each model. The likelihood of the observations under each model is used with Bayes theorem to compute new model weights (Clemen 1996). Models whose predictions are more consistent with data from the monitoring program will receive more weight, whereas weights decrease for models whose predictions do not match monitoring data. Changes in model weights over time provide evidence in favor of one hypothesis over another and a manager can use that new understanding to adjust subsequent decisions based on what has been learned. Managers and biologists should, therefore, choose management actions and monitoring designs with regard to their most pressing information needs, so that putative impediments to achieving management objectives are tested rigorously and early (Lee 1999).

The Roles of Monitoring

In the applied setting of wildlife management, as distinct from the broader setting of wildlife science, monitoring can play $\geq$3 roles: to provide information necessary for state-dependent decision-making, to evaluate management performance, and to facilitate improved management through learning (Nichols and Williams 2006).

System-state variables are specific attributes of the resource that reflect management impacts (e.g., population size, occupancy rate, and area of available habitat). The optimal management action at the time of the decision often depends on the current state of the system. Similarly, there may be a threshold value for a system-state variable, such that a specific value triggers a management action. In both cases, monitoring that will be used for state-dependent decisions should reflect appropriate time scales. Although many management cycles are annual, there are other time frames that may present recurring decision points (e.g., weekly decisions about water levels in managed wetlands).

The management of mallards (*Anas platyrhynchos*) in North America provides a real example of monitoring for state-dependent decision-making and of successful adaptive management in general (Nichols et al. 1995, Johnson et al. 1997). Each year the United States Fish and Wildlife Service (USFWS) uses an optimal state-dependent strategy to determine harvest regulations. The regulations chosen for a given year depend on estimated numbers of ducks and breeding ponds. To inform this decision, the USFWS, Canadian Wildlife Service, and partners monitor waterfowl and wetland abundance over approximately 3.6 million km^2 of breeding habitat in Canada and the United States each year and use observations of resource abundance and habitat conditions to choose an optimal harvest strategy (Nichols and Williams 2006).

The second role of monitoring is to evaluate management performance and determine if actions implemented in the previous management cycle(s) are achieving fundamental or at least means objectives. For monitoring to fulfill this role, management objectives should be quantitative whenever possible and always explicitly stated in advance of any action. Furthermore, indicators of success must be sensitive to management actions and there must be explicit descriptions, made during the planning phase, of how observations will be used for evaluation (Bisbal 2001). For example, management for endangered red-cockaded woodpeckers (*Picoides borealis*) often calls for maintenance of old-growth pine forests (Conner et al. 2001). The fundamental objective in an adaptive management setting could be stated in terms of minimizing probability of extinction or maximizing persistence over some arbitrarily long time frame. Monitoring for this objective would focus on abundance and distribution of woodpecker breeding groups and demographic rates, which would allow decision-makers to evaluate progress toward lowering probability of extinction. Habitat characteristics related to old-growth objectives (i.e., means objectives), might include stem diameter and density distributions, percent grass cover in the understory, and percent hardwood subcanopy. Specific quantitative objectives for these habitat variables could be identified in the planning phase of adaptive management for old-growth conditions, and monitoring plans would be designed to allow accurate measurement and comparison with habitat goals.

A third role of monitoring, in the context of adaptive management, is to provide information necessary to discriminate among competing hypotheses about the managed system, a feedback loop for learning. Note, however, that in the applied context, knowledge is not sought for its own sake, but only insofar as it is expected to improve future management. Monitoring programs should, therefore, focus on the critical uncertainties that may be impeding progress toward management objectives. Managers must anticipate how the monitoring information will be used and choose indicators that are useful for support or refutation of hypotheses about the causes of biological patterns. Sainsbury (1991, Sainsbury et al. 1997) used adaptive management to understand why 2 commercially important species of groundfish were declining. Sainsbury (1991) devised 4 alternative models of the system: 3 hypotheses representing effects of inter- and intraspecific competition and one hypothesis about habitat disturbance as a result of trawling practices, the predominant fishing method. Using formal decision analysis, stakeholders decided to use replicate areas open to trawl fishing and others closed to fishing for a period of ≥ 5 years, the minimum amount of time required to discriminate between hypotheses in this case. Sainsbury et al. (1991) then evaluated the potential for various combinations of trawl versus trap-fishery effort in a management experiment to identify causal mechanisms associated with declines of groundfish populations. Monitoring set up in conjunction with the experiment provided strong evidence in favor of the fourth hypothesis, that trawling negatively impacted groundfish habitat. Thus, Sainsbury provides an example of how multiple working hypotheses and monitoring result in learning (1991, Sainsbury et al. 1997).

MONITORING AND ADAPTIVE WETLAND MANAGEMENT ON NATIONAL WILDLIFE REFUGES

National Wildlife Refuges and the United States Geological Survey (USGS)–USFWS Wetland Management Project

The National Wildlife Refuge System administers 9,653,527 ha of wetlands. Most of these wetlands are within Alaska, USA, and most receive only passive management or protection from degradation by outside threats. However, on refuges within the conterminous 48 states, considerable time and effort is expended to manage 382,903 ha of impounded wetlands. We provide a historical context of wetland management on refuges and introduce our study, a collaboration between USGS and USFWS.

Management of impounded wetlands often entails manipulation of water levels to dependably mimic natural hydroperiods or alter annual hydrology to meet annual life cycle needs of wetland-dependent wildlife (Kaminski et al. 2006). Outside the context of our study, refuge managers annually evaluate the condition of each impoundment, determine appropriate wildlife objectives, identify management strategies to achieve desired habitat conditions, conduct planned treatments, and evaluate success of their efforts (Habitat Management Planning Policy; USFWS 2002). The planning process, however, involves considerable uncertainty about selection of appropriate wildlife objectives and management strategies to achieve desired habitat conditions, optimal timing of manipulations, growth of invasive or undesired vegetation, and trade-offs created by management for a particular taxonomic group. Adaptive management would allow refuge staff to reduce some of these uncertainties and improve management decisions.

Historically, monitoring to evaluate management performance has been conducted to varying degrees at refuges. At some refuges insufficient staff time does not allow monitoring of all factors that may impact success of management actions, whereas at other refuges, inability to replicate management treatments, except through time, often precludes effective evaluation. Lack of evaluation, or collection of insufficient data, often results in perpetuation of ineffective management strategies, missed opportunities to achieve wildlife objectives, and limited understanding of the system being managed.

To reduce management uncertainties, 23 refuges in the USFWS Midwest and Northeast regions with similar wildlife objectives and management capabilities initiated a large-scale management experiment in collaboration with USGS. The study was designed to evaluate aspects of USFWS wetland management practices and provide data, predictive models, and protocols sufficient for refuges to apply adaptive management at the conclusion of the experiment. Participating refuges agreed to conduct consistent management strategies and collect data such that information could be pooled among refuges to provide spatial replication. Refuge staff and USGS scientists collaborated during the design of the monitoring program to assure that management actions and data collection were consistent among refuges, feasible for refuge staff to implement, and most importantly, addressed refuge information needs.

Objectives of the USGS–USFWS Wetland Management Project

The motivation for the USGS–USFWS wetland management project was more informed management of wetlands on National Wildlife Refuges (NWRs) in the Midwest and Northeast regions. In the planning phase, biologists and managers from the 23 participating refuges met with regional managers, regional biologists, and other scientists to identify wetland management objectives. We established 2 fundamental objectives: 1) maximize number of waterbirds (including shorebirds, waders, and waterfowl) during important phases of the annual cycle, and 2) establish and maintain native wetland plant communities. Associated with these fundamental objectives were 4 means objectives: 1) maximize food resources for waterbirds, 2) maximize accessible habitat for waterbirds, 3) minimize extent of nonnative, invasive plant species, and 4) provide germination conditions for native plant species that are important food resources for waterbirds. We believe that it is important to distinguish fundamental from means objectives during evaluation of management performance on refuges because achievement of means objectives (such as providing habitat) without achievement of fundamental objectives (attracting waterbirds) would indicate that our implicit habitat models were inadequate to describe the response of the birds to management.

Recognizing that there are significant gaps in our knowledge of how waterbirds and native plants respond to wetland management, we also identified a number of learning objectives for the study. It is important to note that we formulated these learning objectives to improve future management decisions; they represent key uncertainties in the system dynamics that affect our ability to manage the resource optimally. The responses of waterbirds, invertebrates, and plants to water-level manipulations were sources of structural uncertainty. Refuge staff also desired to understand the trade-offs that exist, if any, between management actions for migratory shorebirds and wetland use by other waterbird guilds throughout the annual cycle. This was a departure from normal management practices at many refuges, where management objectives are often limited to one waterbird group at a specific time during the annual wetland cycle.

Potential Wetland Management Actions

We identified a set of possible management actions that could achieve our objectives and that were feasible for refuges to conduct on an operational basis after the conclusion of the experiment. Our intent was to provide, through management, the varying habitat types that occur during periods of drying and flooding of a natural wetland (Fredrickson 1991). Provision of these habitats was adjusted at each refuge to match the phenology of migration and germination and growing conditions of target plant species. In this manner it is anticipated that the varying needs of several wetland-dependent wildlife groups may be met on the same management unit during different periods of the annual cycle. We identified habitat objectives (e.g., water depths, vegetation structure, vegetation composition, and invertebrate biomass) during different times of the year to meet the needs of each waterbird group. With this framework, we considered 2 fundamentally different water-management strategies (i.e., hydroperiods) that also incorporated potential vegetation management actions.

Our 2 management alternatives provided habitat for either spring- or autumn-migrating shorebirds, with additional hydrologic manipulations at other points in the annual cycle to meet requirements of other waterbird groups (Fig. 1). The primary management action was to conduct a slow drawdown of impoundment water levels timed to meet the peak migration of either spring- or autumn-migrating shorebirds. As drawdowns progressed, we expected food resources to be concentrated into smaller volumes of water to facilitate efficient feeding by postbreeding wading birds. Subsequently, we maintained low water levels to allow for germination and development of annual plant species and later raised or lowered water levels to provide appropriate feeding depths for migrating waterfowl.

In addition to water-level manipulations, we also manipulated vegetation communities when conditions warranted. Vegetation management primarily addressed invasive species that, if left untreated, would result in costly reclamation efforts within the impoundment during subsequent years. We also manipulated vegetation in some impoundments where dense stands of robust vegetation that would influence habitat structure during future years had developed. Primary vegetation management actions consisted of mowing, disking, or spraying with herbicides for some invasive species.

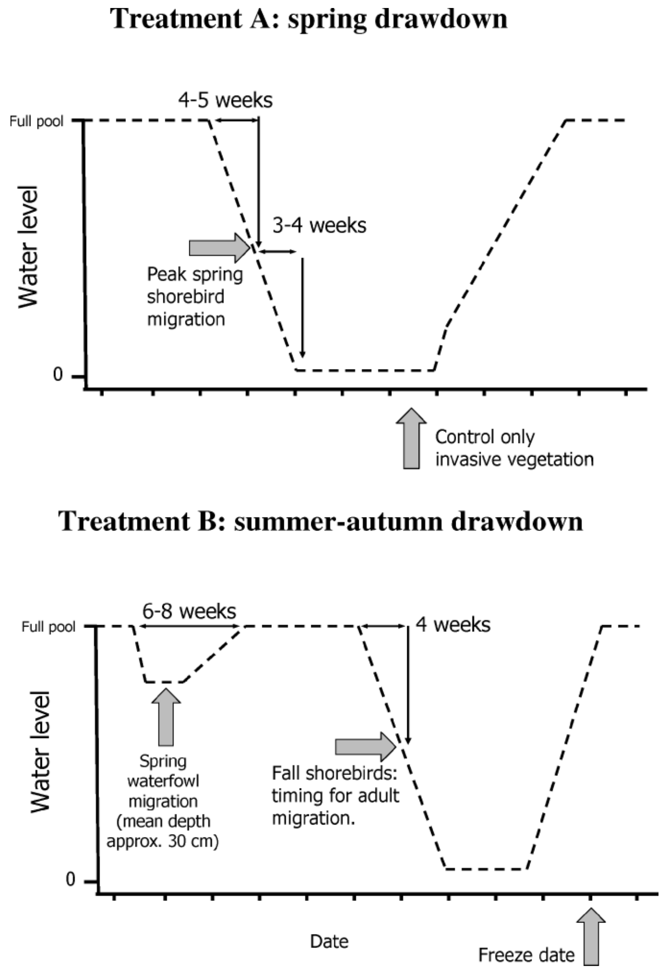

Figure 1. Schematic representation of experimental hydroperiods (treatments) applied in the United States Geological Survey–United States Fish and Wildlife Service wetland management experiment. Treatments A and B provide habitat for migratory shorebirds in the spring and summer–autumn, respectively. Treatment A also provides favorable conditions for germination of annual plants or for management actions to control undesired plant species. The *x*-axis (Date) is not labeled because the timing of water-level manipulations was adjusted at each refuge to match migration phenology.

Study Design

The USGS–USFWS wetland management project was a 3-year management experiment. At each refuge we selected 2 managed wetlands based on water-management capabilities and other criteria. To be included in the study, we required each wetland to have a water source and water-control structure(s) capable of producing a slow drawdown at the appropriate time of year. At each refuge, we attempted to select 2 wetlands that were comparable in size (≥6 ha), free of extensive perennial vegetation, and without a history of mosquito-control operations that could have impacted invertebrate populations. The 3-year sequence at each

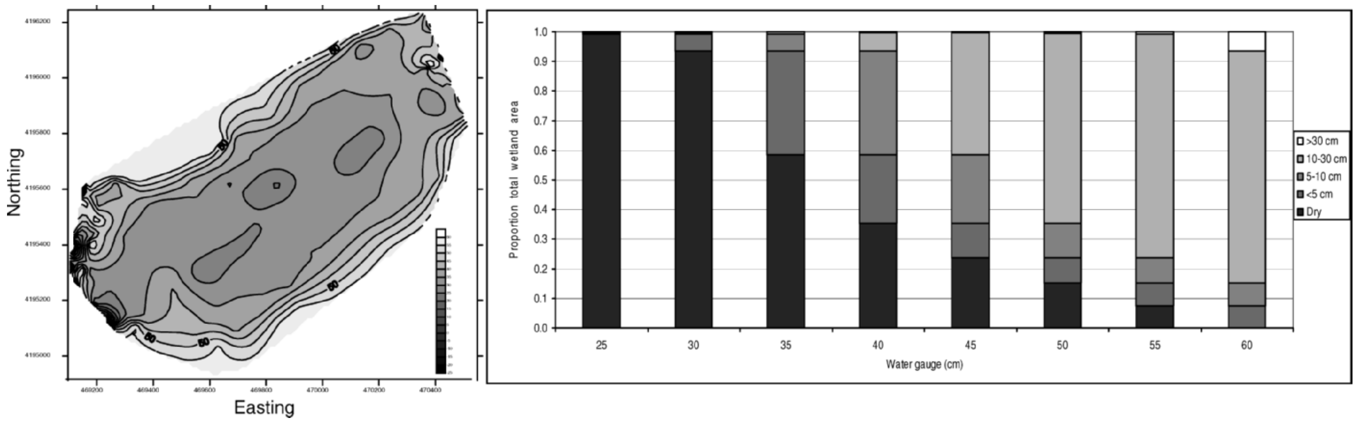

Figure 2. Bottom-contour map (left) and bathymetry chart (right) that were used to set water-level targets and evaluate success in relation to habitat objectives for the B-South wetland at Chincoteague National Wildlife Refuge, USA, 2005. The chart shows changes in the distribution of shallow-water habitat with flooding and draining. For any given water gauge reading (*x*-axis), the height of the bar indicates the proportion of the total wetland area in various depth classes. In this example, optimal shorebird foraging habitat is provided at a water-gauge reading of 40 cm.

refuge began with a random assignment of one of the treatments (spring or autumn drawdown) to one of the experimental units; the remaining unit received the other treatment. We applied the 2 drawdown treatments in a crossover design at each refuge in the first 2 years of the study; the unit that received a spring drawdown in the first year received a autumn drawdown in the second year and vice versa. For the third year of the study, we repeated the treatment that was applied in year 2. By repeating the same treatment, either spring or autumn drawdown, in years 2 and 3, we can begin to understand carryover effects of repeated management actions. Note that the experimental design (i.e., predetermined drawdown sequence for 3 yr) precludes some adaptive decision-making during the course of this study.

Roles of Monitoring in Adaptive Wetland Management

Monitoring for state-dependent decisions.—Historically, wetland and water-management cycles are often annual, and managers may need to decide whether to conduct a drawdown in a given year, and if so, at what season. This type of decision often depends on system-state variables (e.g., extent of target species of emergent vegetation). Traditional wetland management plans often called for a 50:50 ratio of open water:emergent plants, which provide food resources for waterfowl (Weller 1978, 1981; Murkin et al. 1997). If cover of emergent vegetation is $<50\%$, the manager may decide to conduct a drawdown to provide appropriate germination conditions for food plants. Alternatively, the decision of whether to implement a drawdown also may be influenced by the extent of undesired or invasive plant species. In each case, vegetation monitoring would provide the information necessary to make a state-dependent decision that would change the amount of vegetation cover. If the manager decides to use a drawdown, another time scale on the order of weeks or days becomes important for state-dependent decisions. On this time scale, decisions are made about when to initiate the drawdown and the rate of drawdown in the impoundment. This decision may be based on the time of arrival of migratory birds at the location or by the current water level in the impoundment at the time of the decision. These state-dependent decisions require information on migration phenology and current water depths. Waterbird surveys, designed to measure timing of bird movements, and water gauges and bathymetric models (see below), facilitate decisions about timing and rate of drawdowns.

As noted above, we did not make state-dependent decisions about drawdowns on an annual basis; the sequence of management actions was dictated by the experimental design. We were, thus, possibly sacrificing some short-term wildlife objectives with a more adaptive approach for the sake of reducing uncertainties via the designed management experiment ("dual effects of control"; Walters 1986:257). We were, however, able to make state-dependent decisions about initiation date and rate of drawdown each year, decisions that were informed by weekly waterbird surveys and water-level readings. We also made state-dependent decisions about vegetation management and control of invasive species as necessary. Vegetation management decisions did not occur on a regular basis, but rather were decision points identified by biologists in the field. Once a decision point was identified, project leaders from USGS and USFWS and the refuge biologists would evaluate control options, incorporating observations on the state of vegetation cover and structure from a vegetation monitoring program. Balancing the management and learning objectives of the project, and the extent of the undesired plant species, we identified a preferred alternative action for vegetation control and refuge biologists implemented these actions at the appropriate points in the annual cycle.

Monitoring for evaluation of management performance.—Our first fundamental objective was to maximize number of waterbirds during important phases of the annual cycle; an associated means objective was to maximize accessible habitat for waterbirds. To evaluate management performance toward these objectives, we monitored bird abundance using weekly bird surveys from March to November, a period encompassing both spring and autumn migrations of waterfowl and shorebirds and the breeding season of wading birds. Each week observers recorded total number of waterbirds detected in study impoundments, by species if possible. The bird surveys allow us to track changes in bird abundance across most of the annual cycle and compare observations to target levels for each refuge.

To monitor progress towards the habitat (means) objective, we created a bottom-contour map of each impoundment to determine the amount of mudflat and shallow water resulting from water-level manipulations (as measured at a permanent water gauge; Collazo et al. 2002). First we established a permanent water-level gauge in each wetland, referenced to a benchmark to determine water elevations. Observers then recorded water depth measurements and Global Positioning System locations along transects throughout the wetland basin. We analyzed the water-depth measurements and spatial data, which need only be collected once, in topographic mapping software that allowed us to determine the amount of shallow-water habitat during the drawdown and flooding cycles from a reading at the permanent water gauge (Fig. 2). With this monitoring design, we reduce uncertainty due to partial management control because we are able to compare our management intentions (e.g., slow drawdown and water depths $<$10 cm during shorebird migration) with actual management outcomes.

At each refuge, we evaluated the success of management actions using a combination of bathymetry data and water-level and waterbird monitoring (Fig. 3). For example, at Chincoteague NWR, it is difficult to maintain shallow-water habitats throughout the summer months because the wetland units are shallow and have sandy substrates and evaporation rates are high. In many years, the managed wetlands are dry at the time of southward shorebird migration. Therefore, to provide shorebird foraging habitat in the late summer and early autumn, refuge biologists gradually flood available wetland units beginning in late July–early August. The bathymetry model created for the B-South unit (see Fig. 2) allows us to monitor the amount of shorebird foraging habitat actually achieved during each year. In 2005, managers began flooding the B-South impoundment on or around 29 July when the unit was almost entirely dry (Fig. 3). By 11 August, management actions resulted in a substantial portion of the impoundment covered with 0–10 cm water (i.e., water depths providing habitat for both small and large shorebirds). Throughout the month of August, 34–50% of the impoundment provided accessible foraging habitat in the 0–10-cm depth range (Fig. 3). Thus we are confident that the management actions were successful in achieving our means objective at this refuge. What about the fundamental objective? During the same time period, shorebird numbers increased 4-fold and then gradually declined throughout August. Because the peak of shorebird abundance during the migration coincided with the creation of shorebird habitat, we suggest that the management actions were successful in helping us achieve our fundamental objective as well (Fig. 3).

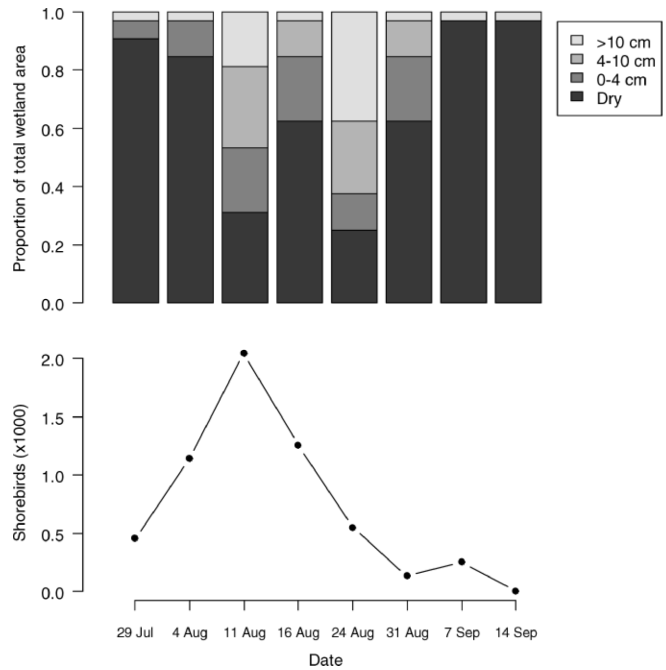

Figure 3. Distribution of mudflat and shallow-water habitats achieved at the B-South wetland at Chincoteague National Wildlife Refuge, USA, in the summer and autumn, 2005. The top panel shows the proportion of total wetland area in various depth classes; the bottom panel shows the shorebird response to management actions. We used combined observations of 1) accessible habitat and 2) shorebird response from the monitoring program to evaluate management performance in relation to means (habitat) and fundamental (bird abundance) objectives.

Other means objectives for our study focus on maximizing food resources available to waterbirds and providing germination conditions for plants that provide food resources to waterbirds. Therefore, we are also directly monitoring benthic invertebrate biomass and density (i.e., shorebird food resources) during spring and autumn migration periods. Finally, we are monitoring vegetation cover, height, and species composition to provide targeted information for evaluating performance relative to these objectives as well.

Monitoring for learning about system dynamics.—In adaptive management, improved understanding of system response to management actions occurs via confrontations between model predictions and observations from the monitoring plan. We are using the 3-year management experiment to build predictive models for future applications of adaptive management on NWRs. Similar to cases of adaptive management, the monitoring design for our experiment is driven by the decision context and targets key uncertainties. Critical uncertainties included responses of waterbirds, invertebrates, and plants to drawdowns at various times of year. Although there is a tradition of wetland wildlife management (Cross and Vohs 1988), much of the available information is of a qualitative nature and strategies are often established as a result of trial-and-error learning, a slow process with little predictive ability (Lee

1999). Several important questions concerning wetland management remain. How do invertebrate biomass and density respond to spring drawdown? Autumn drawdown? Does higher invertebrate abundance result in greater bird use? Are there cross-seasonal interactions in invertebrate response (i.e., does a autumn drawdown this year lead to greater invertebrate abundance next spring)? What is the response of invasive plant species? Can invasive plant populations be controlled with water-level manipulations? Many of these uncertainties concern invertebrate and vegetation responses to very specific hydrologic regimes used in this experiment. We are therefore monitoring 1) plant species composition and vegetation growth, and 2) changes in invertebrate biomass and density at 3 key times in the annual cycle. The targeted observations from this monitoring program will be used to develop predictive models of wetland system dynamics.

Another key uncertainty that was important to wetland managers concerned the trade-offs that may exist between management actions for shorebirds during migration and other waterbirds at other points in the annual cycle, especially migrating and wintering waterfowl. Spring drawdowns that coincide with shorebird migration had little potential to create trade-offs because this sort of manipulation is part of traditional moist-soil management and helps provide waterfowl food plants in the subsequent autumn. It was not clear, however, that habitat management for shorebirds in the late summer and early autumn was compatible with migrating waterfowl objectives. Would the late-season drawdown (Treatment B; Fig. 1) allow enough time for germination of food plants? After a late-season drawdown, would refuges have the capability to flood impoundments to depths favored by waterfowl? We used our weekly bird surveys to address this uncertainty. Many of the refuges in our study strive to provide habitat for waterfowl during autumn migration and winter. From the first 2 years of the experiment, it appears that there is little conflict between shorebird and waterfowl habitat management at the wetlands in our study. Waterfowl abundance in the autumn was similar at wetlands that had been managed for spring and summer–autumn shorebird migration (Fig. 4).

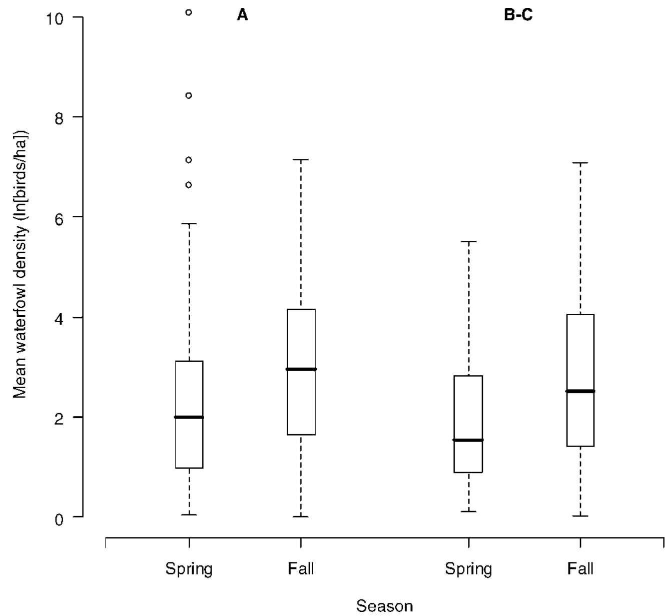

Figure 4. Waterfowl density during spring and autumn migration by experimental hydroperiod (treatment) at 22 National Wildlife Refuges in 2005 and 2006. Treatment A is a spring drawdown. Treatment B–C is either a summer–autumn drawdown or a summer–autumn shallow flooding (target depth 10 cm). Waterfowl density was similar for spring versus summer–autumn water management, indicating little trade-off between manipulations to provide shorebird foraging habitat in the summer–autumn and waterfowl objectives at other points in the annual cycle. The heavy line of each box-plot represents the median; the box encompasses the first and third quartiles, and outliers are shown with open circles.

Summary.—One of the fundamental objectives of wetland management on NWRs was to maximize the number of waterbirds feeding in the impoundments of interest. Therefore we monitor the number and activity of waterbirds that result from our actions. However, what if few waterbirds use an impoundment? What went wrong? If we have only monitored bird numbers and activity, we would not have an answer. However, if we monitor the number of invertebrates and the vegetation abundance and structure, we might find that few invertebrates were produced or that there was too much vegetation for the impoundment to attract certain waterbirds. If in turn we have monitored the distribution of water we might find we were successful in producing the desired distribution (indicating some lack of support for our hypothesis about appropriate water distribution for producing invertebrates), or we might find that water was not distributed as desired (indicating partial control of water distribution as a function of water-control structure manipulation). By monitoring the results of each element in this chain of events, from water manipulation to waterbird use, we can begin to consider separately issues of uncertainty.

DISCUSSION

Wildlife monitoring in a decision setting is unlike monitoring in general. The monitoring design, time and expense invested, and methods used in the field are driven by explicit plans for how the resulting data will be put to use. In this setting, monitoring should be part of structured decision-making and must fill $\geq$1 of 3 roles. When managers and other decision-makers must choose among alternative actions, and when the choice depends on the state of $\geq$1 variable in the managed system, monitoring results should be capable of informing the decision. In addition, monitoring programs should provide information necessary to evaluate progress toward management objectives, which means that objectives must be clearly stated in advance of any actions and before monitoring designs are established. Finally, when decisions will be iterated through time, monitoring produces observations that help discriminate among competing hypotheses about how the system operates (Nichols 1999, Nichols and Williams 2006). Thus, monitoring allows decision-makers to reduce uncertainties about the system and how it responds to management, while simultaneously achieving management objectives.

Adaptive management is a special case of structured decision-making and is not appropriate for all wildlife management questions. Adaptive management requires a series of sequential decisions, a set of models characterizing the breadth of uncertainty about resource relationships and management impacts, and the ability to adjust management actions based on what has been learned (Williams et al. 2007). When these basic conditions are met, we believe adaptive management is the most effective and efficient way to achieve management objectives. When the basic conditions for adaptive management are not met, the broader approach of structured decision-making is appropriate. As the goals and practices of wildlife monitoring programs on public and private lands evolve, there is great opportunity to improve active conservation by placing new monitoring programs within a structured decision framework (Nichols and Williams 2006). Similar to the case of adaptive management, the key to structured decision-making is clear links among management objectives, management alternatives, and monitoring. Adaptive management has been widely recognized as having tremendous potential to solve problems in natural resource management, and calls for implementation of adaptive management are becoming more common (e.g., U.S. North American Bird Conservation Initiative Monitoring Subcommittee 2007, Williams et al. 2007). As interest in adaptive management continues to grow, decision-makers should recognize the distinction between structured decision-making in general and adaptive management in particular to apply the appropriate framework for the decision situation.

Broad-based monitoring not tied to management questions is of little value in a management context. In the USGS–USFWS wetland management project, we designed monitoring plans that would improve wetland management practices on refuges and that were feasible to implement on an operational basis. All of our monitoring was designed to fill 1 of 3 roles for monitoring in the context of structured decisions. Monitoring of water levels and vegetation cover allows state-dependent decisions about drawdown schedules and when to implement vegetation manipulations. Other aspects of our monitoring programs allow us to evaluate management performance because we derived our monitoring targets from fundamental and means objectives (i.e., waterbird abundance, waterbird food resources, and native plant communities). Finally, to increase our understanding about the response of managed wetlands to spring and autumn drawdowns, our monitoring focused on key uncertainties: the response of waterbirds, invertebrate populations, and plant communities to specific water-management prescriptions. Thus, this example serves to illustrate the way in which the management context should drive monitoring design for applied natural resource management problems.

MANAGEMENT IMPLICATIONS

Using the tools of structured decision-making and adaptive management, we have shown how monitoring can be intimately linked with making and evaluating management decisions. By using these tools (clarifying objectives, identifying alternative actions, and making even qualitative predictions about the consequences of management actions), a manager will gain clear insights into what should be monitored (e.g., performance measures related to fundamental or means objectives) and can begin to gauge how much effort will be needed. First, this approach will minimize waste of agency resources by avoiding monitoring efforts that are only obliquely related to wildlife decisions that must be made and evaluated. Second, this approach will permit the manager to more clearly evaluate the trade-off between allocating money and personnel to monitoring versus management actions on the ground. Explicit recognition of the roles monitoring data can play in a management context, and a priori agreement about how monitoring data will influence a particular decision, can lead to custom-designed monitoring protocols that are effective and efficient. We urge managers to adopt this approach to making what are often very complex wildlife management and monitoring decisions.

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