

# Spatial Education: Improving Conservation Delivery Through Space-Structured Decision Making

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## Abstract

Adaptive management is a form of structured decision making designed to guide management of natural resource systems when their behaviors are uncertain. Where decision making can be replicated across units of a landscape, learning can be accelerated, and biological processes can be understood in a larger spatial context. Broad-based partnerships among land management agencies, exemplified by Landscape Conservation Cooperatives (conservation partnerships created through the U.S. Department of the Interior), are potentially ideal environments for implementing spatially structured adaptive management programs.

Keywords: adaptive management; conservation partnership; learning; prairie management; spatial replication; uncertainty

Received: August 9, 2012; Accepted: January 15, 2013; Published Online Early: February 2013; Published: June 2013

Citation: Moore CT, Shaffer TL, Gannon JJ. 2013. Spatial education: improving conservation delivery through space-structured decision making. *Journal of Fish and Wildlife Management* 4(1):199–210; e1944-687X. doi: 10.3996/082012-JFWM-069

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## Introduction

A clear shift in the approach to conservation of species, habitats, and ecosystems in North America has occurred over the past three to four decades. Traditionally, a management agency might independently devote species-focused or habitat-focused conservation efforts on lands under its jurisdiction. However, a succession of cooperative ventures has evolved that strive to achieve landscape-scale or range-wide conservation benefits for entire guilds, communities, or ecosystems through multipartner collaborations. Familiar examples that focus

on bird conservation include the North American Waterfowl Management Plan (NAWMP) and its network of Joint Ventures (partnerships established under NAWMP to help conserve the continent's waterfowl populations and habitats; Williams et al. 1999; U.S. Fish and Wildlife Service [USFWS] 2009), Partners in Flight (partnerships for conservation of landbirds throughout the hemisphere; Carter et al. 2000; Partners in Flight 2010), the North American Bird Conservation Initiative (partnerships for conservation of all native bird species throughout the continent; Andrew and Andres 2002; NABCI International, undated), and the Western Hemisphere Shorebird Reserve



Network (partnerships for conservation of shorebirds throughout the hemisphere; Myers et al. 1987; WHSRN 2012). In 2009, to address conservation challenges posed by climate change, the U.S. Department of the Interior established and dedicated funding toward two national cooperator-governed networks: the Landscape Conservation Cooperatives (LCC) and the Climate Science Centers (CSC; Secretarial Order 3289, U.S. Department of the Interior 2009). Both initiatives emphasize the need for development of tools and frameworks to support decision making, especially when uncertainties exist regarding the response of natural systems to anthropogenic stressors operating at local to global scales.

The central premise of these cooperative ventures is that by linking efforts among partners, more effective conservation delivery can be achieved across larger spatial, temporal, and biological scales compared with what is collectively possible through traditional, individual-based efforts (Yaffee 1998; Wondollek and Yaffee 2000; Higgins et al. 2007). These gains are possible in part due to greater efficiencies of working together across jurisdictional boundaries. However, partnerships across scales also increase understanding about biological processes that would not be possible to easily obtain and effectively share at traditional scales of operation.

Replicating decision making across land units can be a means of rapidly accumulating knowledge about system behavior over a diverse landscape or ecosystem. Usually, such endeavors involve a large, heterogeneous land base that is under the collective control of multiple management agencies. The potential to acquire knowledge in this way is only realized with a strong partnership unified around a common purpose, careful consideration of a candidate set of management actions, a robust set of predictive models, and a well-designed protocol for pre- and postaction monitoring. Thus, a high degree of coordination is required to bring together these elements.

Our objective is to describe how spatial replication can be made to work in a multipartner decision context and how it leads to greater conservation returns for the partnership through enhanced learning. We first provide an overview of adaptive management in the decision-theoretic setting (McFadden et al. 2011; Runge 2011), and we demonstrate how replication in space accelerates the temporal learning process. We next describe three typical contexts in which spatial decision making can be conceived. We present a case study in native prairie restoration to demonstrate the structure and operation of a spatially distributed, learning-centered management application. To our knowledge, this application is the first of its kind in a public partnership setting that links the efforts of independent cooperators at multiple sites under a framework that formally applies learning to future decision making. Finally, we conclude with remarks about other conservation settings to which the principles of spatially structured decision making can be gainfully applied.

### Adaptive Management

Uncertainty erodes management performance, generally defined as the degree to which management actions

achieve desired outcomes (Kendall and Moore 2012). Specific forms of uncertainty are widely recognized in operations research and control theory (Nichols et al. 1995; Williams 2001). The first form, “environmental stochasticity,” is largely uncontrollable and irreducible. For example, specific outcomes of weather events, animal movements, population irruptions or die-offs, and other environmental phenomena can neither be controlled nor forecast with absolute certainty; therefore, sound decision making takes into account some form of the expected influence of these events. Two other forms of uncertainty may be partially reducible through increased monitoring and management effort, but they usually cannot be entirely removed. “Partial observability,” the statistical error in estimating the true status of a resource, can sometimes be reduced through increased sampling effort or development of new technology, but it rarely can be eliminated. Similarly, “partial controllability,” the degree to which an implemented management action misses its intended impact, can sometimes be reduced through tighter controls on how the action is implemented.

In contrast with the above-mentioned three forms, “structural uncertainty” can often be reduced through decision making itself (Walters and Hilborn 1978; Williams and Johnson 1995). Structural uncertainty can be described as the uncertainty about the average response of the system to a given management action. For example, uncertainty about the average rate of population growth under a candidate management action may induce two or more competing predictions (hypotheses) about the population’s expected response to that action (Irwin et al. 2011). When these competing notions are represented as alternative predictive models of system response and are coupled to a program of system monitoring, a basis exists for assessing the reliability of each hypothesis as decisions are made through time. To the degree that one hypothesis gains credibility over successive cycles of decision making, its predictions assert increasing influence on future decisions. Consequently, as uncertainty with respect to the competing models is reduced through time, management performance improves.

The repeated assessment of competing predictive models and the use of that insight to guide future decision making are the essence of adaptive management in its decision-theoretic context (Williams et al. 2009). Because adaptive management is a specific case of structured decision making, it is founded on a few requisite structural elements (Moore et al. 2011; Runge 2011):

1. a recurrent decision is to be made through time;
2. at each decision opportunity, the decision is selected from a fixed set of management alternatives;
3. a statement of measurable objectives drives the selection of a decision;
4. a set of competing predictive models represents uncertainty in the average response of the system to the management decision; and



5. a monitoring program serves to inform the selection of the decision, to measure progress toward the objective, and to assess the predictive performance of the competing models.

### Learning under adaptive management

The relative influence of each model on the current decision is reflected by a credibility or belief weight that is assigned to each model (Nichols et al. 1995). In total, these belief weights constitute a probability distribution across the model set. Thus, a belief weight that approaches 1.0 on a given model reflects high belief in that model and little confidence in the other models. Belief weights are redistributed among the models through time in response to observed evidence for or against each model; as such, they are commonly referred to as the “information state” of the system, tracked through time just as one tracks the actual resource state (Williams 1996; Moore and Conroy 2006).

After a decision action and monitoring of the outcome, belief weights are adjusted through application of Bayes’ theorem (Williams 2001). Bayes’ theorem simply reallocates the total share of belief among the defined set of models in proportion to their likelihoods. Each model’s likelihood quantifies the statistical measure of “closeness” between its prediction of the response and the corresponding observed value. A model’s belief weight is thus updated over time as

$$p_{t+1,j} = \frac{p_{t,j}L_j(x_{t+1})}{\sum_i p_{t,i}L_i(x_{t+1})} \quad (1)$$

Here,  $p_{t,j}$  and  $p_{t+1,j}$  are the belief weights associated with model  $j$  at times  $t$  (before the action) and  $t+1$  (after the action), respectively, and  $L_j(x_{t+1})$  is the likelihood of observed response  $x_{t+1}$  under model  $j$ . The likelihood can take on many functional forms, including familiar forms such as the normal or gamma distributions for continuous data or the Poisson or negative binomial distributions for discrete outcomes. What is important to note is that “closeness” of the observation to its prediction is judged by both the accuracy of the prediction (the numerical agreement between the quantities) and the precision of the observation (the measurement and sampling error involved in estimating resource status; Kendall and Moore 2012). If either is low (accuracy or precision), then the likelihood is low, and its influence on the associated belief weight is reduced.

To illustrate these concepts, suppose that a forest management action is being contemplated that results in a specific fledging rate (proportion of nests for which at least one nestling successfully fledges) of a shrub-nesting bird. However, uncertainty about the effect of this action (perhaps arising from conflicting evidence in the literature or disagreements among experts) results in two competing postulations, or models, of fledging rate: a moderate response of 0.6 or an enhanced response of 0.8. In light of this uncertainty, the decision maker is willing to assign equal initial belief weight (0.5) to both models, giving each hypothesis the same benefit of the doubt. The action is carried out, and response of the bird

population is monitored. Out of five nests sampled, four nests successfully fledged a nestling. Assuming that the binomial distribution is the appropriate sampling distribution for these data (because of the inherent success-fail nature of the data), then the corresponding likelihoods are

$$L_1(x_{t+1} = \{4, 5\}) = \binom{5}{4} 0.6^4 (1 - 0.6)^{5-4} = 0.2592 \quad (2)$$

under the moderate-response model, and

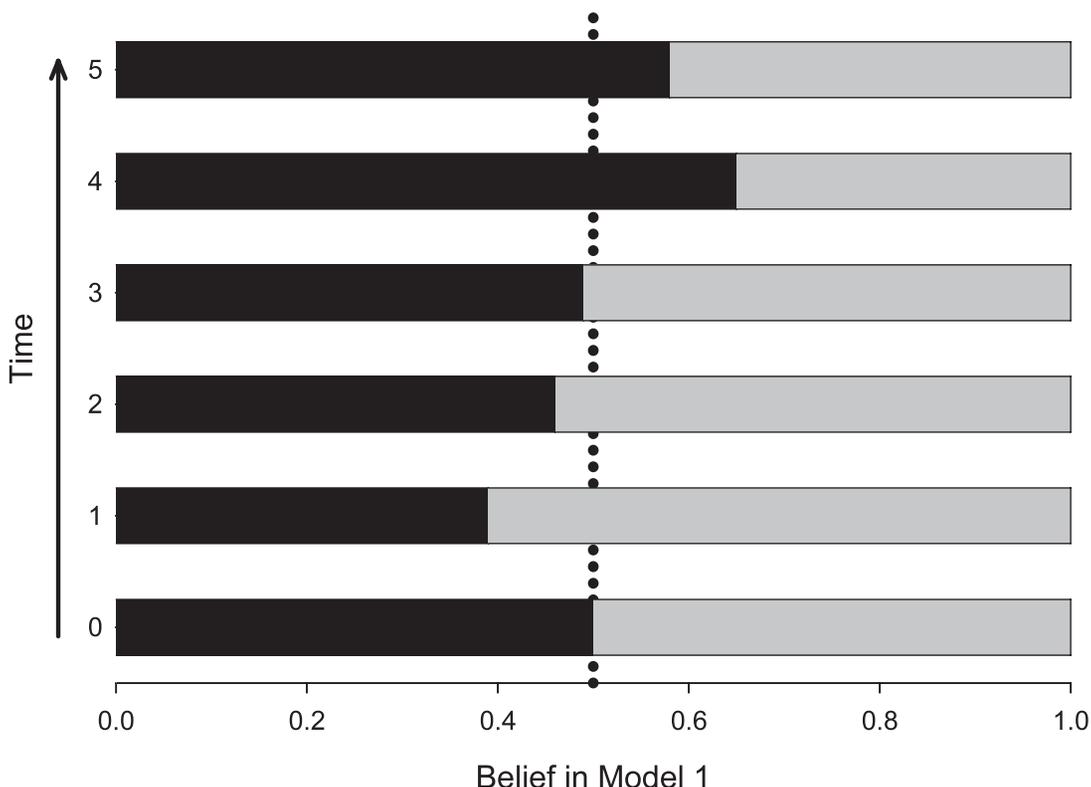
$$L_2(x_{t+1} = \{4, 5\}) = \binom{5}{4} 0.8^4 (1 - 0.8)^{5-4} = 0.4096 \quad (3)$$

under the enhanced-response model. When the likelihoods are combined with the preaction belief weights ( $p_{t,1} = p_{t,2} = 0.5$ ) in Bayes’ theorem, the resultant postaction belief weights are updated to become  $p_{t+1,1} = 0.39$  for the moderate-response model and  $p_{t+1,2} = 0.61$  for the enhanced-response model. Note that although the measured outcome (4 of 5 nests, or 0.8 observed fledging rate) perfectly matched the prediction by the enhanced-response model, that model gained only a modest amount of credibility due to the relatively small sample of nests. Had the sample been doubled and the same fledging rate been observed (i.e., 8 of 10 nests successfully fledged), the evidence for the enhanced-response model would have been greater ( $p_{t+1,2} = 0.71$ ).

In the practice of adaptive management, this process of choosing the action, carrying out the action, and assessing the results is repeated through time, and the outcome of the last decision cycle helps inform the manager of the best action to take in the next cycle (Williams and Johnson 1995). Continuing with the previous example, suppose that the management action is carried out in the same forest patch five times in a row, and assume that the sequence of observations is (4 of 5 nests successful), (11 of 16), (2 of 3), (5 of 8), and (1 of 1). Assuming again that the initial belief weight applied to the two models is  $(p_{t,1}, p_{t,2}) = (0.5, 0.5)$ , then sequential application of Bayes’ theorem results in the progression of model weights ( $p_{t+1,1} = 0.39$ ,  $p_{t+1,2} = 0.61$ ), ( $p_{t+2,1} = 0.46$ ,  $p_{t+2,2} = 0.54$ ), ( $p_{t+3,1} = 0.49$ ,  $p_{t+3,2} = 0.51$ ), ( $p_{t+4,1} = 0.65$ ,  $p_{t+4,2} = 0.35$ ), and ( $p_{t+5,1} = 0.58$ ,  $p_{t+5,2} = 0.42$ ; Figure 1). In this case, model belief weights have not substantively moved from their starting state even by the completion of the fifth decision cycle. Therefore, at the start of the sixth nesting season, uncertainty about bird response is almost as great as it was at the outset of decision making. In natural, noisy systems that are difficult to measure, this result would not be surprising.

### Acceleration of learning through spatial replication

Now, suppose that multiple patches of forest are available (e.g., compartments within a single forest, or management units of different forests) and consider that resources exist to carry out management actions and postaction monitoring on every patch each year. In this circumstance, replicate data on the same type of action



**Figure 1.** Example of model weight reassignment through five cycles of updating from a starting point of equal confidence in model 1 (black) and model 2 (gray) at time 0. Bar length indicates relative belief in the respective models. Uncertainty between the models is reduced to the extent that model belief weight can be driven in either direction away from the 0.5 level of model indifference (dotted reference line).

can be obtained simultaneously, rather than sequentially over time. However, the serial application of Bayes’ theorem remains valid. That is, if the observations (4 of 5 nests successful), (11 of 16), (2 of 3), (5 of 8), and (1 of 1) had been collected on a spatially aggregated set of forest patches receiving the same treatment in a single breeding season, Bayes’ theorem may be applied as if the data had been collected over time. Thus, by this approach, the final set of belief weights is (0.58, 0.42), and as we have noted, this result is not substantially different from the starting belief state; but, unlike the previous example, this result was obtained in a single year. If the same process is applied in a second year, then the amount of learning gained through spatial replication would be comparable with what could be obtained on a single patch over 10 y.

The important limitation to the full interchangeability of spatial and temporal learning is the degree to which spatial replicates are correlated. For example, replicates in which correlations have been introduced by uncontrolled, large-scale temporal effects outside of the direct influence of management actions may be less informative about an action than would be the same number of independent replicates (Dutilleul 1993; Legendre 1993). Therefore, distributing management across widely separated units (relative to the scale of the underlying biological processes) would help to counter these effects and make responses more robust to spatially induced

correlations. Furthermore, a broad-based replication strategy has the advantage of introducing learning-focused management into diverse areas and novel situations, so that biological processes may be understood in a larger spatial context than is traditionally practiced.

There are at least three strategies—experimentation, adaptive management, and a hybrid approach—for model discrimination in a multiple-unit environment (we refer to “unit” as the spatial replicate that receives a management action and follow-up monitoring; unit could refer to, e.g., plots, patches, compartments, impoundments). First, if our purpose is to simply distinguish among models as quickly as possible, and we are willing to forgo management returns in the short-term, then we might seek as many replicate units as possible and randomly assign actions to each unit. Thus, if our immediate focus is on learning, then our best strategy is to design an experiment to efficiently test the competing hypotheses (Johnson 2002). At the conclusion of the experiment when key knowledge has been obtained, the focus would shift from experimentation to management, and we would apply the inferences gained from the experimental work to resource decision making (Williams 1997). Second, we could take a management focus from the beginning and select actions that balance the maximum short-term conservation benefit against the return of information that would increase future

management performance. How these selections are made to achieve this balance is known as the “dual control” problem (Walters and Hilborn 1978; Williams 2001; McCarthy and Possingham 2007), and the trade-off between short-term benefit and long-term performance is explicitly recognized in active adaptive management (Walters and Hilborn 1978). Third, it may be feasible to adopt a hybrid approach, in which some of the units are treated under a management focus (possibly adaptively), but other units are set aside to be treated experimentally (Shea et al. 2002). Compared with adaptive management of all of the units (the second strategy), this approach has a significant drawback in that the “sacrificial” nature of the set-aside units (i.e., their manipulation may yield undesirable management outcomes from which recovery may be difficult) means that these units may have limited direct conservation benefit. Alternatively, the set-aside units ultimately contribute to the overall conservation goal obtainable through the remaining units by providing information that can be rolled into decision making about those units.

### Management Contexts for Multiple Spatial Units

The fact that conservation decision making is often carried out over collections of spatial units suggests that formal decision frameworks could be designed to take advantage of the learning potential offered in such settings. Any of the above-mentioned strategies for model discrimination can be effectively used in one of three common management contexts for multiple spatial units. The contexts differ in the level of partnership across ownerships and administrative structures, and they thus entail different degrees of complexity in how the resource is jointly managed.

The first context is that in which all land units are owned or administered by a single bureaucratic entity, and decisions are chosen by a single decision maker or authority. This setting is the traditional setting for habitat and harvest management and, by far, the most common and simplest management context. The setting can occur in a variety of forms that are related to scale of the problem. For example, a single wetland may be divided into plots to facilitate the trial of different restoration plantings. At a larger scale, a forest may be treated in distinct management compartments, or a coastal refuge may be managed over separate impoundments. At an even larger scale, a state may set harvest quotas and restrictions across a collection of geographically distinct harvest management units.

The second context is that of multiple decision makers or managers operating within a single bureaucratic authority. An example is the USFWS National Wildlife Refuge System (NWRS) and its constituent network of National Wildlife Refuges and Refuge complexes (Curtin 1993; Griffith et al. 2009). The NWRS sets conservation goals at the level of specific ecosystems and populations, and goals are communicated to individual Refuge managers. Refuge managers interpret these goals in the context of the lands under their charge, and the

manager enjoys substantial autonomy in deciding how to approach the goals and which specific actions to take. For Refuges that fall within a specific ecosystem or that provide habitat for a shared population, the potential exists for Refuges to work in cooperation to jointly pursue a common conservation goal.

The third, and generally most complex, context is that of multiple decision makers representing different bureaucratic authorities. For example, an issue such as the conservation of the endangered red-cockaded woodpecker *Picoides borealis* transcends the jurisdictional boundaries of the NWRS, the National Park Service, the U.S. Forest Service, the U.S. Department of Defense, state wildlife agencies, and nongovernmental organizations. Guidance documentation such as the red-cockaded woodpecker species recovery plan (USFWS 2003) provides a blueprint for conservation agencies to individually follow toward the common objective of species recovery. However, with tighter collaboration and coordination among these agencies, such as that envisioned in the LCC model (U.S. Department of the Interior, undated; National LCC 2012), it would be possible to fashion informative decision frameworks to accelerate collective progress toward this objective.

As we discuss later, political environments arising from stakeholders with disparate interests may pose serious obstacles to cooperation, but where they do not, or where they have been addressed in preparatory negotiations, adaptive management may be gainfully used in each of these three contexts. In true partnership arrangements, cooperating stakeholders bring to the table the essential ingredients of adaptive management, including their knowledge and perspectives on desired outcomes (management objectives), feasibility of actions, response of biological systems, and capacity to monitor. Partners also contribute portions of their land base on which actions can be replicated and their consequences followed.

The required structural elements of adaptive management implies a degree of effort and coordination that may be progressively more difficult—but not impossible—to achieve with an increasing number of autonomous decision makers and bureaucratic entities. However, partners provide the skills, energies, and the collective vision needed to design the decision-making process, to seek compromises, and to sustain the process as it moves into routine implementation. For example, agreement on the scale and scope of decision making, the set of quantifiable objectives, and the set of admissible actions may require negotiation and sometimes difficult compromises. Despite the flexibility that can be built into an adaptive management design (as described below in the case study), a multipartner effort may necessitate a partner adopting new perspectives or responsibilities outside of its realm of experience or abandoning others that have been part of management tradition. Furthermore, a suite of requirements, practices, and tools may need to be adopted to ensure that learning can result through comparable efforts across units and jurisdictions. For example, partners must develop and adhere to standardized protocols for applying actions and

monitoring their outcomes. A centralized data system may be necessary to capture and organize cooperator-collected data on actions and responses. Perhaps most importantly, a coordinator must be designated for the care and feeding of the process, including ensuring that cooperators adhere to agreed-upon deadlines and protocols, processing response data to update the decision models, distributing management recommendations to cooperators, and working through implementation problems that arise. Although the investment costs in implementing an adaptive decision framework can be considerable, we believe that they are more than offset by the benefits of a large-scale approach to conservation that is objective, transparent, and strengthened through multipartner cooperation.

### Case Study: Adaptive Management of Native Prairies

We present a case study of an active adaptive management framework—the collection of decision elements, designs, tools, and protocols that process information to yield a decision—that was developed cooperatively among 19 Refuges and Refuge complexes from two administrative regions of the NWRS (Figure 2). Gannon et al. (2012) described an early implementation of this framework. The degree of coordination of efforts was unprecedented for a group of Refuges that have infrequently operated in concert with one another, particularly among those occurring in different regions. In this initiative, a project development team comprised of scientists from U.S. Geological Survey and biologists from NWRS stations worked together to sketch the blueprint for the framework and to assemble the needed technical components. With facilitation from the team, management cooperators representing the participating Refuges negotiated among themselves how the decision support system would be structured, what responsibilities and investments all could agree to take on, and what practices would be followed to ensure consistency and comparability across management units. In turn, the project development team built into the system as much flexibility and user friendliness as possible; often, this flexibility required targeted exercises to elicit expert judgment and advice from the NWRS team members, who acted as delegates for the entire cooperator network. The result was a system that integrates knowledge gained across the network of cooperators and returns it to the individual cooperator in the form of unit-specific management guidance. Because of the investments made by the cooperators, the construction of the decision framework around their needs and constraints, and the understanding that their experiences are directly useable by their colleagues, the participating cooperators have developed a strong sense of ownership of the project.

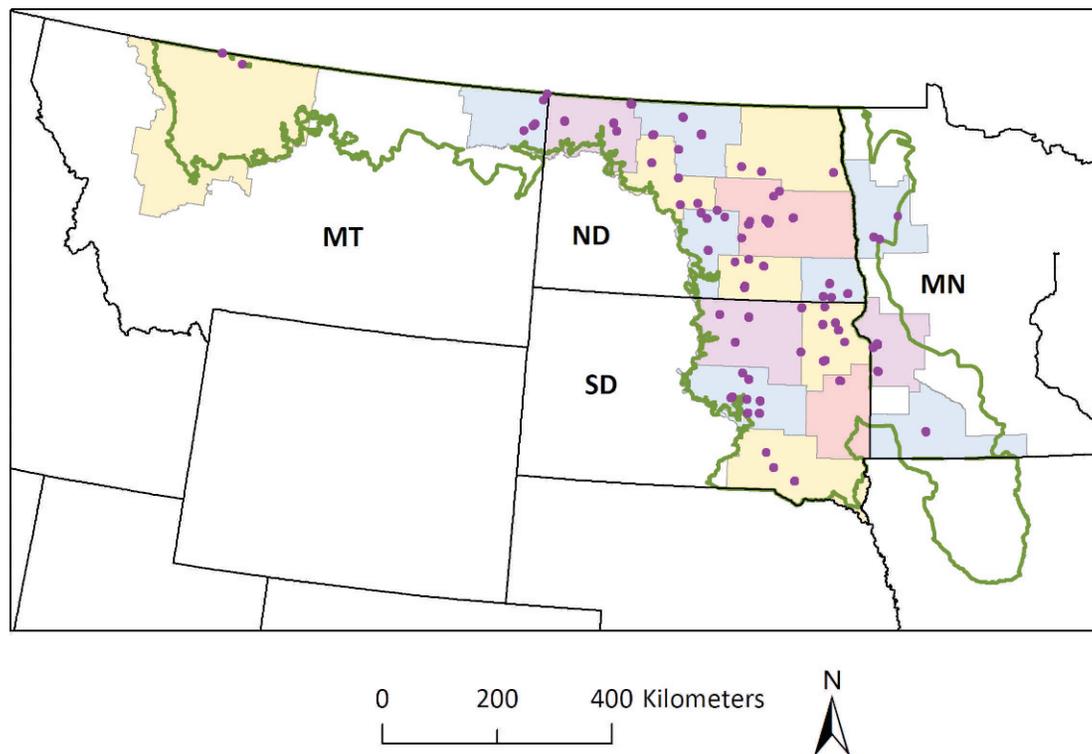
The decline of native grasslands in the northern Great Plains and elsewhere in North America has been well documented (Samson et al. 2004), and the large (>100,000 ha) area of native mixed-grass and tallgrass prairie contained in the land base of the NWRS

constitutes a significant conservation reservoir for this ecosystem. However, a comprehensive assessment of NWRS-owned prairies revealed widespread invasions of introduced cool-season grasses, principally smooth brome *Bromus inermis* and Kentucky bluegrass *Poa pratensis* (Grant et al. 2009). Natural fire and grazing disturbances were evolutionary agents in the formation of native prairies, and the large-scale exclusion of these processes over several decades of NWRS ownership has been implicated in cool-season grass invasions (Higgins et al. 2002; Grant and Murphy 2005; Murphy and Grant 2005). Therefore, Refuges have begun to reintroduce these and other forms of defoliation actions. But attempts to suppress invasive plants on NWRS-owned prairies have met with poor-to-inconsistent success, mainly for limited understanding of prairie restoration ecology, a lack of a coordinated effort among Refuges, and absence of a systematic evaluation of management effects.

A need for a broad-based, coordinated, and information-driven effort to restore native prairies on NWRS lands motivated the Native Prairie Adaptive Management (NPAM) initiative (Gannon et al. 2012). Managers from the participating Refuges convened at a workshop and came to agreement about the spatial focus of management action (parcels of upland native sod that had never been farmed), the decision time step (annual), the management objective (increasing cover of native prairie grasses and forbs on these parcels at least cost), and the set of admissible treatment actions (fire, grazing, fire and graze combination, no action). Achieving consensus on the objective and treatment actions was the most difficult task of the workshop. For example, some expressed desires to consider vegetation structure as well as composition in the objective, or to take into account the animal community response to management. However, the group concluded that these other attributes were secondary to the principal concern about restoring native prairie cover; therefore, the narrower focus on composition was adopted. During the workshop, all participants acknowledged that an unwieldy number of potential treatment options would arise from all possible combinations of action types, intensities, and timing; however, participants also understood that learning about prairie restoration would be compromised if consensus on a small, focused set of options could not be achieved. Therefore, the cooperators settled on the reduced action set described above, agreeing that sufficient uniformity in treatment application could be achieved through adherence to best management practices for each action type, while recognizing that a degree of uncontrolled variability is nevertheless inevitable and should be accounted for in the predictive models and assessment of response.

The goal of NPAM is to support decision making while acknowledging and resolving biological uncertainties. Therefore, the core of the decision structure comprised a set of four predictive models that expressed plausible, alternative hypotheses about how the vegetation community responded to different forms of treatment. The first model proposed that all forms of occasional





**Figure 2.** Extent of the Prairie Pothole Region within the United States (outlined area) and distribution of approximately 120 management units (points) included in the Native Prairie Adaptive Management Initiative, 2009–2012. Management units were selected from 19 stations (approximately corresponding to Wetland Management Districts that are shown as colored polygons) of the National Wildlife Refuge System, and the stations are distributed across four states and two U.S. Fish and Wildlife Service administrative regions.

defoliation are equally effective against either smooth brome or Kentucky bluegrass, at any degree of invasion. This “state-independent” hypothesis is the de facto model that often underlies decision making in prairie management settings within and beyond the NWRs. The second model proposed that defoliation treatments were differentially effective against invasive species type; therefore, identity of the primary invading species influenced the selection of an appropriate action. The third model recognized invader identity, like the second model, but it further postulated that the unit’s defoliation history influenced the efficacy of the next defoliation action. Thus, through past defoliation, a unit could build up sufficient “momentum” to safely intersperse years of rest. The fourth model was in turn built on the third model, but it proposed that efficacy of all defoliation treatments diminished with decreasing cover amount of native grasses and forbs in the unit; that is, below some native cover threshold, actions from the treatment menu are no longer effective, and managers are better served by abandoning or scaling back defoliation management at the unit. Each hypothesis was represented by a state and transition model, in which combinations of input states (cover amount of native vegetation, dominant invader type, defoliation history) and actions yielded probabilistic distributions of output states. We parameterized the models using information elicited from select NPAM team members with extensive experience in the field.

The NPAM decision framework prescribes an annual cycle of activities and relies on the integration and distribution of data between organizational hierarchies (Gannon et al. 2012). The management year spans from 1 September to 31 August, and treatment actions may be applied at any time in the year. Late in each management year (June–August), managers conduct belt-transect sampling (Grant et al. 2004) to assess vegetation composition on each management unit. Information describing the applied treatment and the raw monitoring data are entered into a web-hosted centralized database by 25 August. Meanwhile, the project coordinator queries a set of decision models to generate competing predictions of expected vegetation outcome for each unit given its prior-year vegetation status (composition and defoliation history) and the treatment it received. Immediately after the 25 August deadline, the coordinator uses automated software to compile the monitoring data and to perform a unit-by-unit comparison of the model predictions against the observed outcome. Model belief weights are then updated, making use of each unit’s information as a spatial replicate in the updating step. With the new model weights and the current measurement of vegetation status in hand, the coordinator consults an optimal decision table to find next year’s recommended management action for each unit. This table, computed by an algorithm that accounts for future transitions in vegetation state and model belief weights (i.e., an active

adaptive approach for the acquisition of learning expected as a result of each possible action; Walters and Hilborn 1978), provides an optimal action for each possible model weight assignment and each possible vegetation state that may occur. Thus, the coordinator merely looks up these conditions in the table and discovers the corresponding optimal action. These optimal actions are distributed as recommendations to the cooperators by 1 September for implementation during the following management year. This schedule provides managers lead time to prepare burn plans and grazing contracts for the coming year. Managers make the ultimate decision about the action applied; it is at their discretion to follow the recommended action or to choose an alternative from the set of available options. Currently, approximately 120 spatial units are managed under this framework (Figure 2).

To illustrate the process of learning through NPAM, we provide results for a sample of five management units from 2010, the first year of NPAM implementation (Table 1). Values of native cover amount, dominant invasive species, and defoliation history were recorded for each unit in August 2009, and an action was carried out during the subsequent year (Table 1). In August of the following monitoring year (2010), state values were again recorded (Table 1). Upon observing these responses, we obtained a likelihood for each model by integrating transition probabilities from the predictive models across estimated sampling distributions for the observed states (Table 1). Before decision making under NPAM, we established initial model belief weights of  $p_{t,1} = p_{t,2} = p_{t,3} = p_{t,4} = 0.25$  to reflect our indifference about relative credibility among the models. We used Bayes' theorem and the model likelihoods to update these weights. Although it is feasible to perform updating in unit-by-unit succession as we described earlier, we instead computed medians of the likelihoods across units and performed model weight updating with the median values. The reasons we did so are beyond the scope of this paper, but the salient points are that learning about prairie vegetation response to treatment is assimilated across all units and knowledge about system behavior is enhanced with more units. Based on median likelihoods computed for these five units (Table 1), model weights were updated as follows:

$$p_{t+1,1} = (0.218 \times 0.25) / L = 0.253 \quad (4)$$

$$p_{t+1,2} = (0.178 \times 0.25) / L = 0.206 \quad (5)$$

$$p_{t+1,3} = (0.208 \times 0.25) / L = 0.241 \quad (6)$$

$$p_{t+1,4} = (0.259 \times 0.25) / L = 0.300 \quad (7)$$

where  $L = (0.218 \times 0.25) + (0.178 \times 0.25) + (0.208 \times 0.25) + (0.259 \times 0.25) = 0.216$ . For all 66 units for which data were available in 2010, the updated model weights were  $p_{t+1,1} = 0.277$ ,  $p_{t+1,2} = 0.228$ ,  $p_{t+1,3} = 0.243$ , and  $p_{t+1,4} = 0.252$ . Thus, knowledge was incrementally

acquired through this management cycle and translates into updated influence by each model on the subsequent management recommendations.

The NPAM decision framework clearly requires a highly coordinated, standardized, and thoroughly documented effort on the part of Refuge cooperators. To this end, every detail of the scheme either was negotiated among the cooperators, made use of their existing capabilities, or was designed around their constraints. For example, cooperators preferred to have their deadline for data entry delayed as late as possible and the coordinator's deadline for delivering management recommendations advanced as early as possible; ideally, for the cooperators, the deadlines would occur on the same day. Understanding these desires, the project development team hired software developers to create database and analytical tools that largely automated the processes of data compilation, updating, and optimal decision lookup; these tools in turn allowed the time span between the two deadlines to be kept to a reasonable minimum of 7 d (25 August–1 September). As another example, the development team redeployed an efficient, sustainable, and robust monitoring protocol that had been used in an earlier project (Grant et al. 2009) and that was a technique already familiar to many Refuge cooperators. Furthermore, cooperators were familiar with each of the treatment actions, and no action entailed any specific setup or application outside of a cooperator's range of experience. Finally, because cooperators cannot always carry out the action that is recommended (a form of partial controllability), an optimal decision table that is derived by ignoring this uncertainty can produce management recommendations that rely on unrealistic patterns of future management behavior. Therefore, the development team explicitly accounted for this source of partial controllability in the production of optimal decision tables. Ultimately, tailoring the process around the capabilities and constraints of partners makes it more likely that the process can be sustained over many cycles of decision making. This consideration is crucial in applications of sequential decision making for dynamic resources, particularly those that are adaptive, as these efforts require long-term commitment by partners and their administrators (Moore et al. 2011).

### Extensions to Other Cooperative Efforts

To our knowledge, the NPAM initiative is the only operational implementation of a design that uses both spatial and temporal replicates to drive learning in a decision-theoretic, active adaptive management framework, but we believe that others will soon appear. The NPAM initiative is an example of the second context of decision making for multiple units, in which the units are under the control of multiple decision makers from a single bureaucratic entity. Future work under this project may include approaching potential non-NWRS partners and testing the portability of the framework to other land management agencies.

The approaches in NPAM can be extended to other settings where adaptive management can benefit from



**Table 1.** Initial states (amount of native prairie cover, dominant invasive grass species, and defoliation history), implemented action, outcome vegetation states (amount of native prairie cover, dominant invasive grass species), and computed likelihoods under four models of vegetation dynamics for five selected management units from North Dakota and South Dakota participating in the Native Prairie Adaptive Management program, 2009–2010.

Unit <sup>a</sup>	Initial states (2009) <sup>b</sup>			Action implemented <sup>c</sup>	Outcome states (2010)		Model likelihood <sup>d</sup>			
	% Cover native vegetation	Dominant invasive species	Defoliation history		% Cover native vegetation	Dominant invasive species	Model 1	Model 2	Model 3	Model 4
1	30–45	KB	High	Graze	0–30	KB	0.218	0.161	0.067	0.076
2	30–45	SB	Medium	Rest	30–45	SB	0.259	0.267	0.319	0.325
3	0–30	KB	Medium	Burn/graze	0–30	KB	0.482	0.178	0.208	0.373
4	45–60	SB	Medium	Rest	60–100	SB	0.217	0.206	0.256	0.259
5	30–45	CO	Low	Burn	45–60	CO	0.068	0.083	0.147	0.060
Median							0.218	0.178	0.208	0.259

<sup>a</sup> Units: (1) Arrowwood Complex Topp East (North Dakota), (2) Arrowwood Complex Odegaard (North Dakota), (3) Huron WMD Millerdale 2 (South Dakota), (4) Lostwood Complex Lake Zahl (North Dakota), (5) Sand Lake Complex Cooper North (South Dakota).

<sup>b</sup> State classes: Percentage of cover native vegetation (0–30, 30–45, 45–60, 60–100%), dominant invasive species (SB = smooth brome, KB = Kentucky bluegrass, CO = codominant smooth brome and Kentucky bluegrass), defoliation history (low, medium, or high levels reflecting frequency and recency of defoliation in previous 7 y).

<sup>c</sup> Actions chosen from following set: rest (no defoliation), graze, burn, or burn/graze combination.

<sup>d</sup> Models recognize treatment efficacy either as independent of state (model 1); dependent on dominant invasive species type only (model 2); dependent on dominant invasive species type and defoliation history only (model 3); or dependent on native cover amount, dominant invasive species type, and defoliation history (model 4). Likelihoods result from integration of state transition probabilities across estimated sampling distributions for the observed states.

spatial replication, including multipartner cooperatives. Habitat restoration efforts, such as the NPAM initiative, are well suited for a spatial replication approach. Efforts targeting the control of specific invasive plant or animal species also may be good candidates. For example, the consideration of alternative stand-level treatments for forests invaded by hemlock woolly adelgid *Adelges tsugae* or by Chinese privet *Ligustrum sinense* may be effectively structured in an adaptive, multiunit decision framework. Likewise, alternative techniques in the reintroduction of threatened or endangered species could potentially be cast in a multiunit decision framework. For example, the consideration of alternative release strategies to reintroduce a rare salamander could involve efforts distributed across different patches of suitable habitat. Decisions about harvest of game species that occur in discrete population units also may be amenable to a spatially-structured approach. For example, a state may make harvest decisions about American alligators *Alligator mississippiensis* in each of a number of harvest management units; learning derived from the spatial replication of these decisions can help to inform management in subsequent years.

In any of these settings, two or more partners can pool their resources and cooperatively engage to improve conservation benefit for all participants. “Partners” are generally public agencies, nongovernmental institutions, or units of a single bureaucracy, but in some cases, such as in private lands programs, they can be private citizens. With programs such as the Conservation Reserve Program (U.S. Department of Agriculture), the Partners for Fish and Wildlife Program (USFWS), and other private lands programs, each private landowner is in partnership with the sponsoring agency, where landowners apply to receive some form of incentive or benefit in return for

carrying out agreed-upon conservation practices. The landowners act independently of one another, but the process of selecting landowners for participation (enrollment) could be designed in a decision analytical framework so that information learned from efficacy of past enrollments assists the sponsoring agency in awarding future enrollments (Howell et al. 2009). In this way, with each round of decision making, the partnership network becomes increasingly effective at accomplishing program-wide conservation goals.

Because of their common mission and the gravity of their shared problem, participants in NPAM understood the imperative to work cooperatively and were able to coalesce around a management objective, alternatives, and a framework design. Admittedly, this degree of cooperation and consensus is often rare in many multipartner situations, particularly as geographic scope or stakeholder diversity widens. A difficult task in structured decision making is reconciling among multiple objectives that stakeholders may bring to the table (Converse et al., in press). However, formal techniques for eliciting preferences and evaluating trade-offs among objectives greatly simplify this task for partners who act in good faith (Keeney and Raifa 1976; Keeney 1992; Goodwin and Wright 1998). Thus, if parties are able to apply one of these techniques to arrive at a consensus objective, then adaptive management should be feasible. Far more intractable is the situation where partners do not act in good faith or are totally inflexible to compromise, perhaps encouraged by a political environment that induces a collaboration that is forced, unfocused, unnatural, and ultimately unwelcome. We argue that such cases of dysfunction are more properly considered in the arena of conflict resolution and that any formal, analytical process of structured decision making, including adaptive

management, is destined to fail until these conditions can be rectified (Lee 1993; Gregory et al. 2006). Our approach, like any science-based decision-making approach, is limited in practice to those situations in which stakeholders come to the table in good faith, can rally around or at least find common ground in a unifying consensus objective, and can agree on a statement of the critical uncertainties.

### Summary

Partnerships among and within land management agencies offer the potential to enhance conservation delivery through the ability to replicate decision making across land units under collective control of partners. By carefully coordinating the efforts of partners and managing the information that is generated, learning can be accelerated and refocused toward future decision making.

Partner-based decision frameworks can be structured to address issues across the conservation spectrum, including habitat restoration, endangered species recovery, harvest management, invasive species control, and reserve design. Our experience in the NPAM initiative suggests that although assembling a spatially replicated decision framework may require a substantial effort to overcome logistical and technical challenges, a coordinated conservation partnership pays important dividends. First, as already noted, the distribution of decision making over replicate land units accelerates learning and management performance, but it also informs understanding of variability in response over a heterogeneous landscape. Second, partners develop a deep stake in the process and outcome due to several factors: a clear purpose unites the partnership, partners play unambiguous and visible roles, development of the framework is a participatory and input-driven process, and partners understand how their investments benefit themselves and others in the partnership. Finally, by demonstrating how to work across administrative boundaries and to seek collaborations that span traditional chains of command, participants can begin to appreciate how other conservation problems may be fruitfully approached via partnerships.

### Supplemental Material

Please note: the *Journal of Fish and Wildlife* is not responsible for the content or functionality of any supplemental material. Queries should be directed to the corresponding author for the article.

**Reference S1.** NABCI International. Undated. About NABCI: all birds, all habitats. NABCI International, Washington, D.C.

Found at DOI: <http://dx.doi.org/10.3996/082012-JFWM-069.S1>; also available at [http://www.nabci.net/International/English/about\\_nabci.html](http://www.nabci.net/International/English/about_nabci.html) (43 KB PDF).

**Reference S2.** [National LCC] National Landscape Conservation Cooperative. 2012. Landscape Conservation Cooperatives: frequently asked questions. National Landscape Conservation Cooperative.

Found at DOI: <http://dx.doi.org/10.3996/082012-JFWM-069.S2>; also available at <http://www.doi.gov/lcc/upload/LCC-FAQs-Final-2012.pdf> (3.4 MB PDF).

**Reference S3.** Partners in Flight. 2010. What is Partners in Flight (PIF)? Partners in Flight.

Found at DOI: <http://dx.doi.org/10.3996/082012-JFWM-069.S3>; also available at <http://www.partnersinflight.org/description.cfm> (85 KB PDF).

**Reference S4.** U.S. Department of the Interior. 2009. Secretary's Order 3289: Addressing the impacts of climate change on America's water, land, and other natural and cultural resources.

Found at DOI: <http://dx.doi.org/10.3996/082012-JFWM-069.S4> (3.5 MB PDF).

**Reference S5.** U.S. Department of the Interior. Undated. Interior's plan for a coordinated, science-based response to climate change impacts on our land, water, and wildlife resources.

Found at DOI: <http://dx.doi.org/10.3996/082012-JFWM-069.S5>; also available at <http://www.doi.gov/csc/upload/Detailed-LCC-and-CSC-Information.pdf> (123 KB PDF).

**Reference S6.** [USFWS] U.S. Fish and Wildlife Service. 2003. Recovery plan for the red-cockaded woodpecker (*Picoides borealis*), 2nd revision. U.S. Department of the Interior, USFWS, Atlanta, Georgia.

Found at DOI: <http://dx.doi.org/10.3996/082012-JFWM-069.S6>; also available at <http://www.fws.gov/rcwrecovery/files/RecoveryPlan/finalrecoveryplan.pdf> (1712 KB PDF).

**Reference S7.** U.S. Fish and Wildlife Service. 2009. North American Waterfowl Management Plan.

Found at DOI: <http://dx.doi.org/10.3996/082012-JFWM-069.S7>; also available: <http://www.fws.gov/bird/habitat/NAWMP> (269 KB JPG).

**Reference S8.** [WHSRN] Western Hemisphere Shorebird Reserve Network. 2012. WHSRN: an international strategy for saving shorebirds and their habitats. Western Hemisphere Shorebird Reserve Network.

Found at DOI: <http://dx.doi.org/10.3996/082012-JFWM-069.S8>; also available: [http://www.whsrn.org/sites/default/files/file/WHSRN\\_general\\_fact\\_sheet\\_\\_12\\_06-11.pdf](http://www.whsrn.org/sites/default/files/file/WHSRN_general_fact_sheet__12_06-11.pdf) (1710 KB PDF).

**Reference S9.** Williams BK, Szaro RC, Shapiro CD. 2009. Adaptive management: the U.S. Department of the Interior technical guide. Washington, D.C.: Adaptive Management Working Group, U.S. Department of the Interior.

Found at DOI: <http://dx.doi.org/10.3996/082012-JFWM-069.S9>; also available: <http://www.doi.gov/initiatives/AdaptiveManagement/index.html> (38.1 MB PDF).

### Acknowledgments

We thank P. J. Heglund and M. G. Knutson who invited us to present our ideas at a symposium organized at the 2011 Annual Conference of The Wildlife Society. We also thank the members of the NPAM team, particularly the cooperators whose efforts and continued interest sustain



the program. S. Jacobi and V. Hunt of the Chicago Botanic Garden created the database and web interface tools that integrate and automate the decision support process. We thank B. J. Irwin, A. J. Tyre, D. R. Smith, Subject Editor M. Post van der Burg, and an anonymous reviewer for critical comments that improved our manuscript.

We received support for the development of NPAM through grants from the USGS-USFWS Refuge Cooperative Research Program, USFWS Region 6, and USGS Northern Prairie Wildlife Research Center. Before submission, this manuscript received approval through the USGS review process and, thus, its contents are consistent with all pertinent policies of the USGS and the U.S. Department of the Interior.

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