RESEARCH ARTICLE

Crisis on the Prairies Revisited: Implementation of the Native Prairie Adaptive Management Program

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ABSTRACT

The U.S. Fish and Wildlife Service (Service) is a primary manager of federal public lands in the northern Great Plains region, with over 400,000 hectares (ha) of mostly grassland and wetland administered under the National Wildlife Refuge System (NWRS). More specifically, the Service manages > 100,000 ha of mixed-grass and tallgrass prairie in northern Great Plains states. Prairies range from small, isolated < 16-ha tracts embedded in agricultural landscapes to > 10,000-ha contiguous tracts embedded within grassland-dominated landscapes. The mission of the NWRS is uniquely wildlife/wildland oriented, with human uses secondary in importance. As such, the expectation is that natural plant communities occur as relatively high-quality habitats. Grant et al. (2009) explored this expectation, concluding that "Despite 40–70 years of protection, the integrity of many prairies held in public trust continues to decline, primarily because of invasion by cool-season, introduced plants and woody vegetation." To address this concern, the Service proposed a program to evaluate restoration of Service-owned prairies following principles of adaptive management, including a decision support function. Our purpose in this paper is to update 14 years of development and implementation of the Native Prairie Adaptive Management (NPAM) program. We confirmed that Service-owned prairies continue to be degraded by invasive plants, especially *Bromus inermis* (smooth brome) and *Poa pratensis* (Kentucky bluegrass). However, NPAM has facilitated a significant gain in our understanding of ecological restoration and management of prairies in the region, increasing hope that restoration successes can occur when viewed over the long-term (i.e., many decades).

Keywords: invasive species, Kentucky bluegrass (*Poa pratensis*), prairie management, restoration, smooth brome (*Bromus inermis*)

The U.S. Fish and Wildlife Service (Service) manages over 400,000 hectares (ha) of grassland and wetland habitat on units of the National Wildlife Refuge System (NWRS) within the Prairie Pothole Region (PPR) of Montana, North Dakota, South Dakota, Minnesota, and Iowa. The mission of the NWRS is to administer a national network of lands and waters for the conservation, management and, where appropriate, restoration of the fish, wildlife and plant resources and their habitats within the United States for the benefit of present and future generations of Americans. The Refuge Improvement Act of 1997 established management standards for the NWRS, including an emphasis on maintaining and restoring biological integrity, diversity, and environmental health (Gergely et al. 2000).

Our focus in this article is native prairie (i.e., remnant grassland tracts without a previous cropping history), a smaller subset of all Service-administered grassland properties. In the northern Great Plains region, biological diversity of native prairies (hereafter prairies) is substantially modified from that of pre-Euro-American settlement (Samson and Knopf 1994). Biological diversity of prairies is compromised by processes and conditions on the larger landscape including agriculture, climate change, urbanization, energy development, invasive plants, fire suppression, and certain grazing practices (Samson et al. 2004, Askins et al. 2007, Grant et al. 2020a). Loss of biodiversity has implications for critical ecosystem services in the region, specifically ecological integrity, wildlife species and habitats, pollinators, nutrient cycles, and hydrologic systems (Ellis-Felege et al. 2013, Toledo et al. 2014, Grant et al. 2020a).

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Restoration Recap

- *Bromus inermis* (smooth brome) and *Poa pratensis* (Kentucky bluegrass) are primary invaders on U.S. Fish and Wildlife Service-owned prairies in the northern Great Plains, as confirmed by an inventory.
- The U.S. Fish and Wildlife Service partnered with the U.S. Geological Survey to develop the Native Prairie Adaptive Management (NPAM) program that coordinates restoration efforts towards achieving a common objective, helps managers make transparent and scientifically based management decisions in the face of recognized uncertainties, and reduces these uncertainties by learning from management actions and outcomes, thereby improving future decision making.
- NPAM has been successfully implemented for over a decade, demonstrating valuable learning, adaptation of management actions with the learning, and progress towards the objective of increased cover of native plants.
- Collaborations between practitioners and scientists continue to foster the success of NPAM, resulting in a capable delivery mechanism both for prairie restoration and scientific understanding that circumvents many limitations of traditional approaches.

Within the northern Great Plains, historically widespread grazing by native herbivores coupled with frequent fires was nearly eliminated following Euro-American settlement (1880–1915). From 1915 through the 1940s, agricultural conversion of prairies accelerated, and remaining prairies were increasingly grazed, mainly by domestic livestock. After acquisition and addition to the NWRS, Service-owned prairies generally were managed with a combination of no grazing or season-long grazing at low stocking rates, and suppression of wildfires continued (Murphy and Grant 2005, Grant et al. 2009). During the 1960s, grazing of Service-owned prairies was further reduced to provide undisturbed nesting cover for prairie ducks and upland game birds. From the 1970s to the 1990s, wildfire suppression continued; interest in prescribed fire was growing, but applications were infrequent (Dixon et al. 2019, Smith 2020). During the past 25 years, prescribed fire and grazing have been more frequently and extensively applied, often in response to invasive plant issues, although this convention has not been universal across Service-owned prairies. Service-owned prairies have collectively experienced decades of deferment from grazing and fire, which is a significant departure from the historical conditions and formative ecological processes under which grasslands evolved and has resulted in decreased biological diversity throughout the region (DeKeyser et al. 2009 and 2013, Printz and Hendrickson 2015, Dixon et al. 2019, Coleman 2022).

More than 100,000 ha of two grassland ecosystems—mixed-grass and tallgrass prairie—are managed by the Service in the PPR stretching from Iowa to northcentral Montana. These prairies range from small isolated < 16-ha tracts on waterfowl production areas within agricultural settings to > 10,000-ha contiguous tracts on National Wildlife Refuges located within grassland-dominated landscapes. Agricultural conversion of many privately owned prairies continues at a rate unlikely to sustain landscape-level biodiversity in the region (GAO 2007, Stephens et al. 2008, Gage et al. 2016, Wimberly et al. 2017). As the overall extent of northern Great Plains prairies dwindles, protected public lands play an increasingly important role in perpetuating representative examples of native plant communities and their animal associations (Murphy and Grant 2005, Grant et al. 2009).

Habitat goals and objectives for Service-owned prairies require periodic review of the biological potential for prairie maintenance or restoration. Grant et al. (2009) proposed a three-phase approach to address this need. In Phase I, floristic inventories were described for a subset of Service-owned prairies in North Dakota and South Dakota (Murphy and Grant 2005, Grant et al. 2009). Inventory data provide a snapshot in time of the contemporary condition of prairies across a broad geographical landscape that differs in soils, topography, and climate. Phase II outlined development of a process, founded on principles of adaptive management, to address the role of *Bromus inermis* (smooth brome) and *Poa pratensis* (Kentucky bluegrass) as the most significant invasive plant threat to Service-owned prairies. Authors proposed using a decision support framework with competing models that capture uncertainty to increase overall understanding of how competition among native and introduced plants affects long-term potential for ecological restoration. Phase III proposed implementation and subsequent long-term operation of what would become the Native Prairie Adaptive Management (NPAM) program. Our objective in this paper is to revisit each phase proposed in 2009 and provide an update on 14 years of NPAM development, implementation, and operation. We describe lessons learned for implementing a large-scale adaptive management program, progress toward meeting our NPAM objectives, and opportunities to learn through auxiliary targeted research.

Phase I: Inventory Service-Owned Native Prairies in North Dakota and South Dakota

Murphy and Grant (2005) described a floristic inventory of prairies for two National Wildlife Refuges located in mixed-grass prairies of northwestern North Dakota (Table 1; Drift Prairies). Grant et al. (2009) later described floristic

Table 1. Floristic composition (percent cover), based on mean values for each comparative era of inventory. The Full Study includes all Service-owned prairies in North Dakota, South Dakota, and northeast Montana, including those of the Dakota Complexes and Drift Prairies (Grant et al. 2020a). Dakota Complexes include five Service-owned administrative complexes in North and South Dakota (Grant et al. 2009). Drift Prairies describe prairies within the glacial drift plain physiographic region located at J. Clark Salyer and Des Lacs NWRs (Murphy and Grant 2005). Low shrubs are primarily *Symphoricarpos occidentalis* (western snowberry) and *Elaeagnus commutata* (silverberry). Weedy forbs are predominantly *Melilotus* spp. (sweet clover), *Euphorbia esula* (leafy spurge) and *Cirsium arvense* (Canada thistle).

Variable	Full Study	Dakota Complexes	Drift Prairies
Years	1999–2008	2002–2006	1999–2002
Hectares	80,494	44,635	4,300
Transects	*n* = 15,144	*n* = 7,438	*n* = 713
Plant Group/Species			
Native grass-forb	24.8	27.6	20.4
B. inermis	29.2	22.8	28.1
P. pratensis	25.4	25.9	20.0
Low shrub	10.3	16.5	22.8
Weedy forbs	0.1	3.8	8.2

inventories for a broader subset of Service-owned mixed-grass prairies in North and South Dakota (Table 1; Dakota Complexes). Grant et al. (2020a) completed inventories for all Service-owned prairies (> 90,000 ha) in the Dakotas and northeastern Montana (Table 1; Full Study). Across the full inventory effort, data were collected during 1999–2008 on 15,144 transects located within 862 mixed-grass and tallgrass prairie units (see Grant et al. 2020a, 2020b for methods).

The inventories revealed that Service-owned prairies were significantly degraded by invasion of introduced grass and forb species and by native species of shrubs, mainly *Symphoricarpos occidentalis* (western snowberry) and *Elaeagnus commutata* (silverberry); however, most notable was the invasion by *P. pratensis* and *B. inermis* (Table 1; Figure 1). Grant et al. (2020a, 2020b) additionally described features associated with spatial variation in the floristic composition observed. Patterns of *B. inermis* and *P. pratensis* invasion varied corresponding to historical patterns in precipitation and temperature, as well as with certain edaphic, topographic, and landscape features such as habitat edges. *B. inermis* and *P. pratensis* were found to have dissimilar relationships to these abiotic and landscape features (Grant et al. 2020b) while also responding differently to grazing and fire; thus, the reduction in one undesirable species may result in replacement by another invader species rather than native plants (Hendrickson and Lund 2010). This conundrum poses significant restoration challenges for managers entrusted with conserving biological diversity of prairies.

Phase II: Develop an Adaptive Management Framework to Guide Restoration of Service-Owned Prairies

Service-owned prairies differ by grassland ecosystem, geographic location, tract size, degree of invasion, soils, etc., making their management an inherently complex undertaking (Grant et al. 2009, 2020a, 2020b). It remains unclear to prairie managers what strategies are most likely to favor native plants in prairies variably invaded by introduced grasses, weedy forbs, and woody vegetation. Additionally, managers face operational constraints as they make decisions about management of prairies, and restoration success is further hindered by a lack of coordinated effort across broad geographical and administrative boundaries. The focus of Phase II was to develop an adaptive management framework to help guide restoration of Service-owned prairies (Grant et al. 2009). To begin this effort, workshops were held starting in 2006 to better understand the ecology of prairies within the region and specifically the invasion biology of *B. inermis* and *P. pratensis*. In 2008, the Service partnered with the U.S. Geological Survey (USGS), expanded the collaboration to Service-owned prairies in Minnesota, and began development of NPAM as the adaptive framework for managing prairies on Service lands (Gannon et al. 2013). From a programmatic standpoint, NPAM coordinates local restoration efforts, incorporates uncertainties that make management difficult, helps managers make transparent and scientifically based management decisions in the face of these uncertainties, and reduces uncertainties by learning from management actions and outcomes, thereby improving decision making and management through time (Gannon et al. 2013).

The adaptive management framework for NPAM includes two primary stages (Figure 2). The setup stage consists of foundational components that were developed between 2008 and 2010. The iterative stage consists of recurrent steps of the annual decision-making process (Williams et al. 2009, Gannon et al. 2013), which were implemented after completion of the setup stage. Here, we briefly describe the development of the NPAM framework. Both the setup and iterative stages are inherently complex, and many details are beyond the scope of this paper; readers can consult additional resources for further information

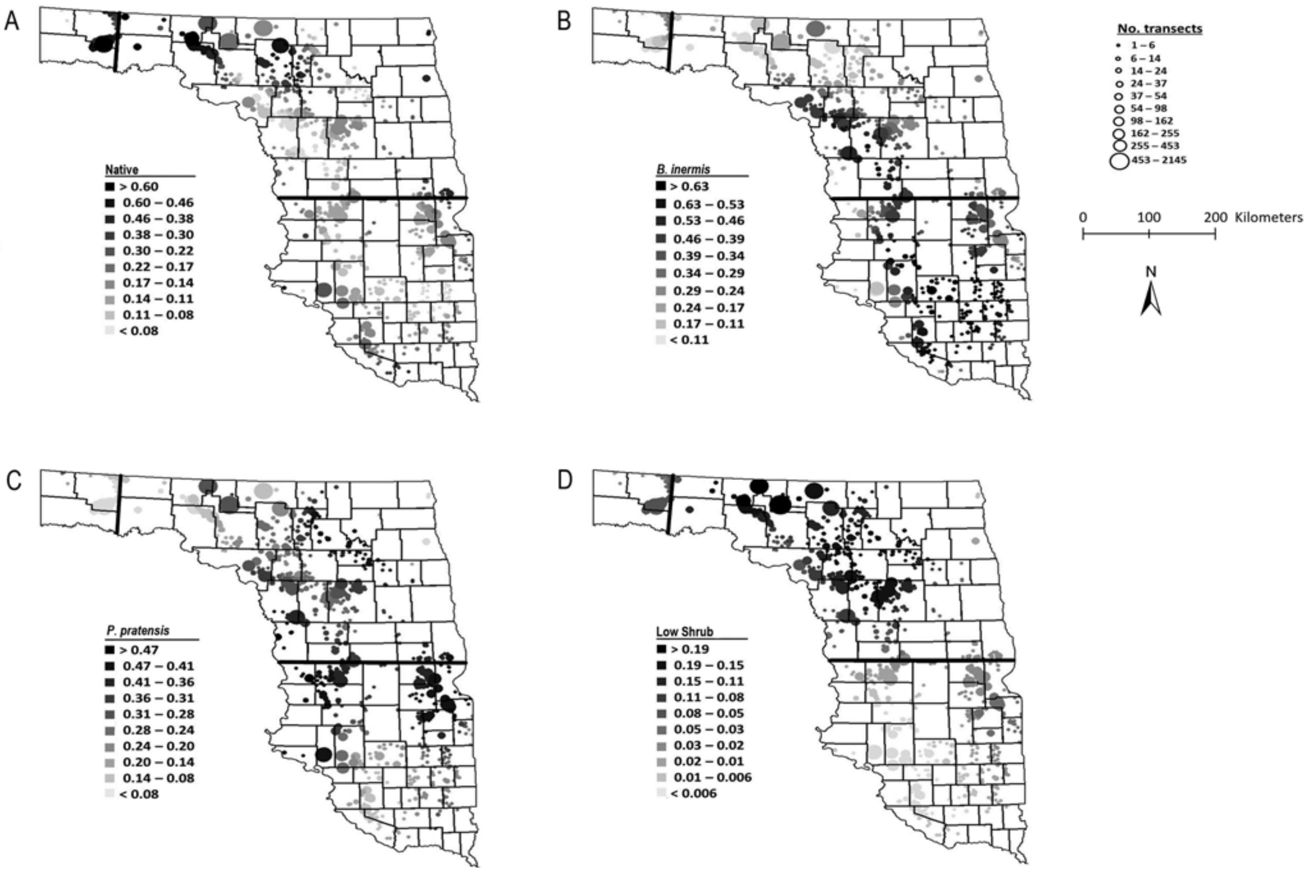

Figure 1. Relative frequency of occurrence for A) native grass-forb, B) *B. inermis*, C) *P. pratensis*, and D) low shrub categories occurring on Service-owned prairies in North Dakota, South Dakota, and northeast Montana. Increasingly darker shading reflects an increasing frequency of occurrence. Increasingly larger circles reflect increasing size (ha) of prairie units composed of a greater number of transects. Counties are represented by solid lines. The division between the three states is indicated by a thicker solid line (adapted from Grant et al. 2020a: figure 2).

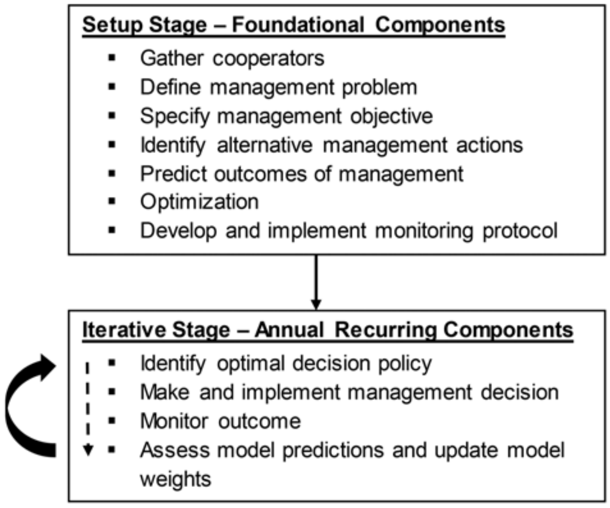

Figure 2. Two stages of the Native Prairie Adaptive Management framework: the setup stage and the iterative stage. The setup stage consists of the foundational components of the decision framework that were developed between 2008 and 2010. The iterative stage consists of the recurrent steps of the annual decision-making, monitoring, and updating process.

(Gannon et al. 2013, Moore et al. 2013, Hunt et al. 2016, Moore et al. 2020).

The NPAM Setup Stage—Foundational Components

The first task in the setup stage was to gather cooperators and identify units to enroll. In 2008 we gathered managers and biologists from all Service districts and refuges in the PPR with native prairie to discuss adaptive management, get buy-in, and begin development of the framework. This effort included representatives from Montana, North Dakota, South Dakota, and Minnesota, the two grassland ecosystems, and two Service regions—Regions 3 and 6 (Figure 3). These cooperators selected units for enrollment. Eligible units included the following criteria: prairie where the major plant of concern is *P. pratensis* and/or *B. inermis*, units capable of receiving a single management action over its entire extent each year, units capable of being monitored each year, and units greater than six ha in size.

The group of cooperators defined the management problem as the loss of native plants, primarily to *P. pratensis* and *B. inermis*, and the uncertainty regarding best management

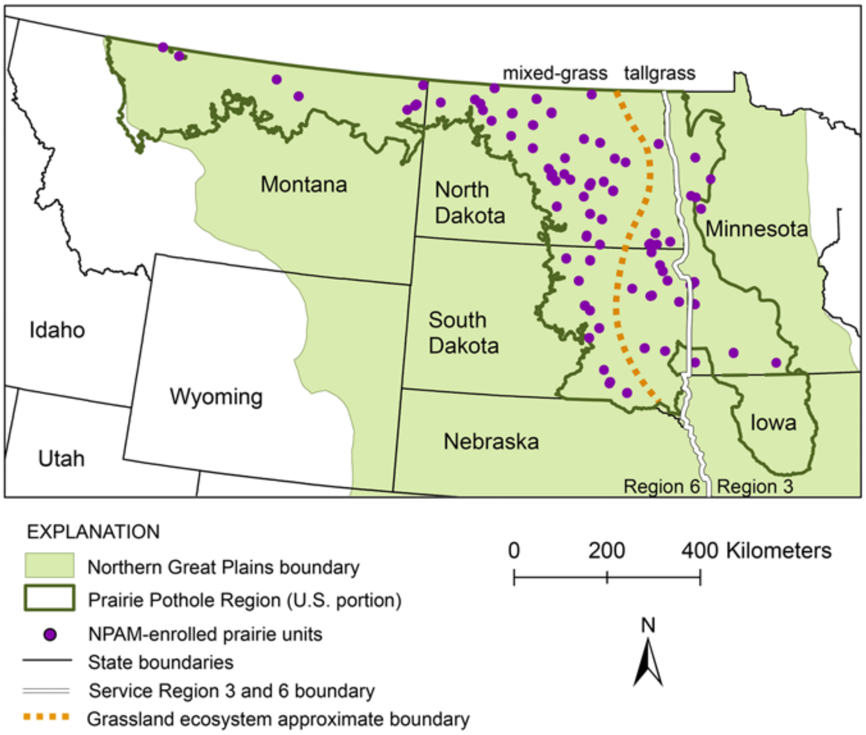

Figure 3. Extent of the mixed-grass and tallgrass prairies within the northern Great Plains of the United States. The dashed line is the approximate demarcation of the mixed-grass (westerly) and tallgrass (easterly) grassland ecosystems. NPAM-enrolled units (*n* = 127) are located within the U.S. portion of the Prairie Pothole Region in Montana, North Dakota, South Dakota, and Minnesota, which includes two Service regions (3 and 6).

practices to restore these prairies. They agreed on the overarching objective of NPAM to increase the cover of native grasses and forbs on prairie while minimizing the cost of restoration. The group identified the set of annual management actions available to achieve the objective, which varied by grassland ecosystem: rest (no defoliation), graze, burn, and burn/graze combination for mixed-grass prairies; and rest and specifically timed grazes and burns for tallgrass prairies. These simple sets of available actions were necessary to ensure replicability of actions and the ability to learn about the effects of these actions on prairie plant response (Moore et al. 2020).

Developing an adaptive management framework required making predictions of management outcomes. We identified primary uncertainties in managing prairies as hypotheses characterized by competing models. The hypotheses are additive in nature such that each subsequent model incorporates the structure of prior models, but with the addition of a new focal postulate. In this way, the comparison of subsequent models allows one to isolate the new focal question. The first model hypothesized that all forms of defoliation (i.e., graze, burn, burn/graze combination) are equally effective, regardless of prairie condition, and result in a more desired native cover than does a rest treatment. A second model hypothesized that the dominant invader (*P. pratensis* or *B. inermis*) results in differential management effectiveness of treatments. A third model added the concept that defoliation history (how recent and frequent) of prairies results in differential management effectiveness, while a fourth model made the additional prediction that degree of invasion by *P. pratensis* and/or *B. inermis* results in differential management effectiveness. Though evaluated separately, mixed-grass and tallgrass prairies share the same structure of the first four models. Tallgrass prairies included two additional models that focused on a specific phenological window of plant growth (see Willson and Stubbendieck 2000 and Gannon et al. 2013). These two additional models shared the same structure as the third model, but they varied in their prediction regarding effectiveness of grazing within the phenological window when *B. inermis* is dominant (fifth model) and effectiveness of defoliation actions outside of the phenological window compared to rest (sixth model).

We defined the current state of a prairie unit by its vegetation composition and defoliation history. We recognize four discrete states of native prairie cover (60–100%, 45–60%, 30–45%, and 0–30%) and four invasive dominance categories (*P. pratensis, B. inermis*, co-dominant *P. pratensis-B. inermis*, and other non-desirable plants), which results in 16 potential vegetation states. Defoliation history is captured by an index devised of how recent and frequent non-rest actions took place over the previous seven years; the index is then broken into three defoliation history levels of low, medium, and high. Additionally, we recognize three timeframes that describe the number of years since a prairie unit last received a non-rest action: one year ago, two to four years ago, and five or more years ago. Feasible combinations of the three defoliation history levels and the three timeframes result in seven potential defoliation history states. Combining the 16 vegetation and seven defoliation history states produces 112 prairie states in which a prairie unit can occur at any point in time.

With the prairie state structure in hand, we converted the hypothesized conceptual models into an explicit quantitative format. The models are state transition probability models that predict probability of change in the prairie vegetation state in response to the alternative management actions, given the starting vegetation state and defoliation history level. A single model consists of 12 16 × 16 vegetation transition matrices, one matrix for each combination of the three defoliation history levels and four management actions (Gannon et al. 2013). Due to lack of available data and published studies on the response of native and invasive plants to management actions, we parameterized the predictive models using expert knowledge (Gannon et al. 2013). We quantified uncertainty through weights of confidence attached to each of the competing predictive models. Having no basis to judge the relative merit of the models at the outset of the program, we captured our uncertainty regarding which competing model best represented prairie response to management by assigning an equal weight of 0.25 to each of the four mixed-grass models and an equal weight of 0.167 to each of the six tallgrass models. Through the annual collection of monitoring data, this set of confidence weights on the competing models changes through time and reflects the current knowledge state.

In addition to the competing predictive model set, the decision framework includes a quantification of partial controllability. A management action that is carried out is not always the targeted or intended action. Circumstances such as unfavorable weather conditions, lack of resources, unpredictable access to burn crews or grazing contractors, for example, can influence the choice of action and make it impossible to fully control what action is implemented. We recognize and quantify the degree of management control through a separate model of partial controllability (Gannon et al. 2013).

We translated our verbal objective into a quantifiable format with a utility function (Gannon et al. 2013). The utility function captures the value cooperators associate with making a one-year gain, loss, or no change in native cover given the starting level of native cover and the management action implemented. Because actions incur costs, the utility function reflected satisfaction with the conservation return for the expense.

An optimization process was used to identify the best management action. We used adaptive stochastic dynamic programming to determine the optimal state-based management guidance expected to return the largest accumulation of utility values over the long run (Gannon et al. 2013). The optimization process combines the competing predictive models, partial controllability model, and utility function to identify the best management action for a prairie unit to achieve the stated objective, given its current vegetation and defoliation history state and the current weight on each of the competing models. The output of the optimization process is a decision table that contains the optimal management action for every possible combination of vegetation, defoliation history, and knowledge state.

As the last ingredient of the setup stage, a monitoring protocol was necessary to determine current prairie composition on each management unit, evaluate progress toward the management objective, and assess predictive performance of each competing model relative to the others. NPAM adopted the modified belt-transect sampling method that was used for the inventory described in Phase I (Grant et al. 2004).

The NPAM Iterative Stage—Annually Recurring Components

To begin each annual cycle of NPAM, we use our current knowledge state (i.e., the weight on each of our competing models) to identify the current optimal decision policy (Figure 2). The decision policy identifies a single optimal management action for each of the 112 prairie states (Gannon et al. 2013). The optimal actions are then provided to cooperators by September 1 of each year as site-specific recommendations for the current state of each enrolled unit for the upcoming year.

Upon receiving the recommendation for each enrolled NPAM unit, land managers consider the recommendation, along with other relevant information (e.g., funding constraints, access to a burn crew or cattle contractor, fuel load, weather conditions, etc.), and decide which of the available actions to implement that year. The decision to carry out the recommendation, as well as the details of the implementation (e.g., timing and intensity), is at the discretion of the land managers. The need for actions outside of the NPAM framework, such as tree removal or spot herbicide application for non-focal invasive plant species, is also at the discretion of the land manager. The details of all actions implemented are recorded. The chosen management action is implemented between monitoring events, sometime between September and the following August.

During July and August of a given growing season, Service personnel monitor NPAM units using modified belt transects (Grant et al. 2004). Cooperators enter their vegetation and management data into a standardized database uploaded to a centralized repository (Hunt et al. 2016) for analysis and subsequent generation of the next year's management recommendations.

Prediction and monitoring are the means to reduce uncertainty about managing prairies. After managers select and implement management actions (either those recommended by the decision policy or one of the other available actions), the predicted outcomes of vegetation state made by competing models are compared to the actual outcome observed via monitoring, and the weights on each competing model are updated using Bayes Theorem (Gannon et al. 2013). Competing models that make predictions closer to the observed outcome garner weight, while those that make poorer predictions lose weight. With the updated

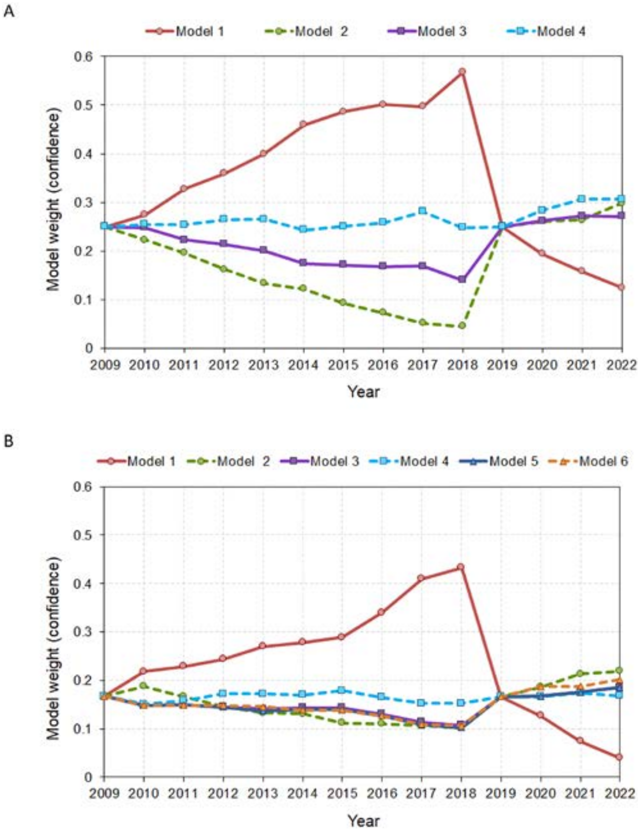

Figure 4. Relative weights for the A) four competing mixed-grass models and the B) six competing tallgrass models as they change across annual updating cycles between 2009 and 2022. In 2009, beginning weights on the competing models were set equal at 0.25 and 0.167 for mixed-grass and tallgrass, respectively. In 2020, after revising model parameters with empirical data from 2009–2019, model weights for 2019 were set to equal and annual updating cycles started anew with the 2019–2020 paired data. The competing models represent primary uncertainties in managing prairies and were parameterized and evaluated separately by grassland ecosystem. Model 1 hypothesizes that all forms of defoliation are equally effective, regardless of prairie condition, and result in a more desired native cover than does a rest treatment. Models 2 through 4 are additive in nature such that each model incorporates the structure of the prior model, but advances a new premise regarding treatment effectiveness; the models focus on the impact of dominant invader, defoliation history, and invasion level, respectively. Tallgrass prairies included two additional models that share the same structure as Model 3, but vary in their prediction regarding effectiveness of grazing within the phenological window when *B. inermis* is dominant (Model 5) and effectiveness of defoliation actions outside of the phenological window compared to rest (Model 6).

knowledge state, we return to the first step of the Iterative Stage and identify the new optimal decision policy.

Phase III: Implement the Adaptive Management Framework

Enrollment and monitoring in the NPAM program began in 2009. Service cooperators from 19 stations enrolled in the program, including 81 mixed-grass and 39 tallgrass units that are located across North Dakota, South Dakota, Minnesota, and Montana and span two Service administrative regions—3 and 6. The first recommendations from the decision support framework were provided for each NPAM unit in 2011. In 2016, enrollment in NPAM was opened to non-Service agencies within the PPR whose management problems and objectives aligned with those of NPAM and whose units and participants could fulfill all aspects and protocols of NPAM enrollment (Gannon et al. 2013). Currently, NPAM includes approximately 120 Service units, six units managed by Audubon North Dakota, and one unit managed by North Dakota Game and Fish Department (Figure 3).

Evaluating Hypotheses—Part I

At the start of NPAM, with no evidence to favor any model over the other, we assigned equal belief to each of the competing four mixed-grass and to each of the six tallgrass models. Over a nine-year period (2009–2018) of developing and implementing the NPAM framework, we saw annual shifts in the model weights that discriminated amongst the competing models in terms of their performance and their influence on the annual decision policy from which the annual management recommendations are derived (Figure 4). For both mixed-grass and tallgrass prairies, we saw growing support for Model 1, while Model 4 maintained its initial weight, and all other models lost weight. The tallgrass model set showed poorer discrimination through the years compared to the mixed-grass model set, due in part to a larger model set and smaller sample size of units.

Adapting Management Based on Learning—Part I

Each year, all competing models contribute to the updated annual decision policy according to their current respective weights. We present the decision policy—the optimal action to take under current conditions of percent composition by native prairie, primary invading species, defoliation level, and years since last defoliation—as a color-coded look-up table (Figure 5). The policy can change each year as belief weights assigned to the models change. Model 1, the simplest model for both grass types, ignores prairie unit state of dominant invader, defoliation history, and invasion level, and it recommends use of the cheapest non-rest management on a five-year cycle. The increased

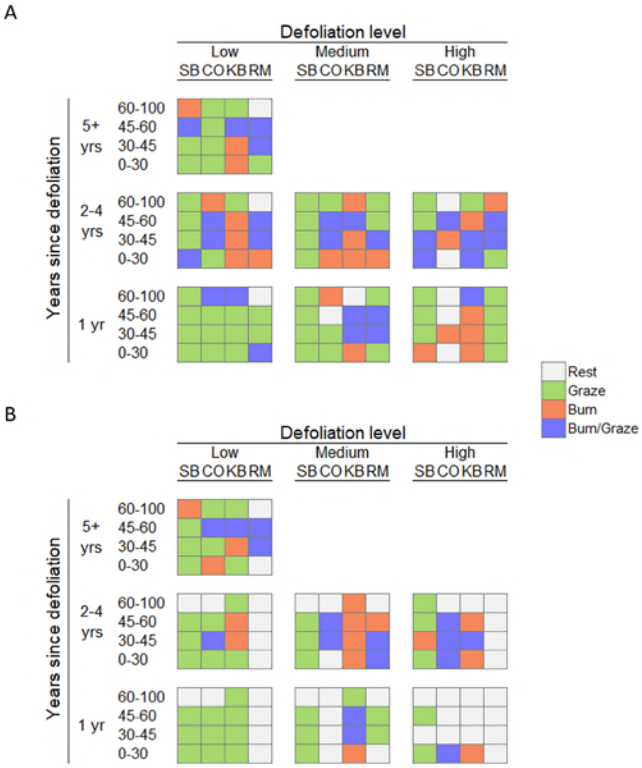

Figure 5. Mixed-grass decision policies of management recommendations based on expert-derived parameterized models. The two decision policies reflect A) equal weights of 0.25 first assigned to each of the four competing models in 2009 and B) updated weights of 0.56, 0.05, 0.14, and 0.25 on the four competing models in 2018 that evolved after nine annual updating cycles (2009–2018). The decision policy indicates the optimal management action (rest, graze, burn, or burn/graze combination) given the current state of a prairie unit and the current weight on the four competing models. The current state of a prairie unit is defined by its vegetation composition and defoliation history. We recognize four discrete states of native prairie cover (60–100%, 45–60%, 30–45%, and 0–30%) and four invasive dominance categories (SB=smooth brome, CO=co-dominant smooth brome and Kentucky bluegrass, KB=Kentucky bluegrass, RM=remainder), which results in 16 potential vegetation states. Defoliation history is captured by an index of how recent and frequent non-rest actions took place over the previous seven years; the index is then broken into three defoliation history levels of low, medium, and high. Additionally, we recognize three timeframes that describe the number of years since a prairie unit last received a non-rest action: one year ago, two to four years ago, and five or more years ago. Feasible combinations of the three defoliation history levels and the three timeframes result in seven potential defoliation history states. Combining the 16 vegetation and seven defoliation history states produces 112 prairie states in which a prairie unit can occur at any point in time.

weight and influence of Model 1 over the years (Figure 4) resulted in a decision policy that called for fewer active treatments and more rest treatments across the possible 112 prairie states (Figure 5b) than did the original policy that was derived from equal influence of all four models (Figure 5a), or than would policies derived from gains in influence by the other competing models.

Revising Model Predictions Based on Expert Elicitation with NPAM Data

During the design of NPAM we did not have data on which to base the predictions of the competing models. For this reason, we used expert elicitation as the basis for the model predictions (see Gannon et al. 2013 for methods). From the inception of NPAM, we intended to update or replace the expert-elicited predictive models with predictions based on observed responses once we had accrued enough data (i.e., paired consecutive monitoring years × number of units).

After seven annual cycles (i.e., paired consecutive years of monitoring data that include pre- and post-monitoring events with an intervening management action) of following the framework, we had acquired sufficient empirical data to assess the accuracy of the elicited predictions of prairie response to management. Predictions were well aligned in some cases; however, in other cases, predictions were in the same direction but off in magnitude of response, or they differed in direction of response. The most notable differences occurred in effects of rest, graze, and burn treatments in mixed-grass models. For example, experts greatly overpredicted the positive effect of rest treatments in co-dominated prairies and graze treatments in smooth brome-dominated prairies, while greatly underpredicting the positive effect of burn treatments in Kentucky bluegrass-dominated prairies (Supplementary Material, Tables S1–S3).

With adaptive management, newly acquired data discriminate amongst the existing competing models to reveal the best performing model within the set. However, while a model in the set may be "better" relative to others in the set, it may not accurately reflect prairie response to management (i.e., there may be more accurate but unknown models we did not consider). Despite being a poor predictor of actual prairie response to management, Model 1 garnered the most weight among the set of competing models over the years for both mixed-grass and tallgrass (Figure 4). Model 1 is the simplest model (fewest parameters), and though the predictions were inaccurate, its predictive performance outpaced the more complex models (i.e., those with more parameters). Having more parameters would seem to offer greater ability to accommodate patterns in the data; however, quantity of parameters does not help if the quality of those parameters is poor.

The comparative analysis between the elicited and empirically-derived predictions made it clear that it was necessary to revamp our NPAM decision framework by

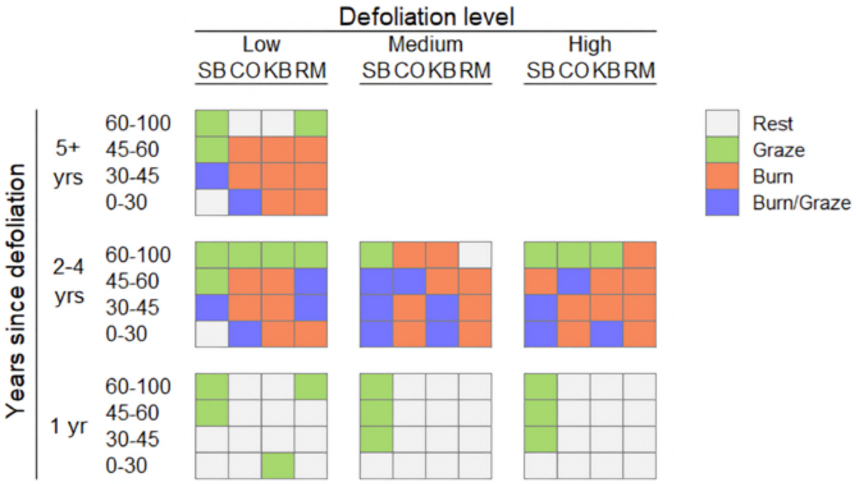

Figure 6. Mixed-grass decision policy of management recommendations based on empirically derived parameterized models built in 2020. The decision policy reflects equal weights of 0.25 on each of the four competing models. Figure design and components are the same as those in Figure 5; see Figure 5 caption for further description.

replacing expert-derived model parameters with those that were empirically derived (see Moore et al. 2018 for methods). We revised the predictive models for both mixed-grass and tallgrass in 2020, using the 10 annual cycles of data (2009–2019) that had been collected up to that point. As part of the revision, the structure and main hypotheses of the competing models, which we believe remain valid, were maintained; only the parameters of the predictive models were changed. Concurrently, we took the opportunity to revise the partial controllability model with parameters derived from empirical data. Revising the modeling and partial controllability components of the framework required re-optimization to derive new decision tables that identify the optimal management for every prairie state, now based on improved predictive models and estimates of partial controllability.

Evaluating Hypotheses and Adapting Management Based on Learning—Part II

Because we used our initial 10 annual cycles of data to revise framework components, it was reasonable to reset the 2019 weights of the competing models to an initial state of equal confidence across all models in the set for each grassland ecosystem. When comparing the revised decision policy (Figure 6) to the original decision policy (Figure 5a), with model weights set to equal confidence in both cases, we saw more burn and fewer graze recommendations. This shift in recommendations parallels the comparisons between the elicited and empirically based predictions regarding burn and graze effectiveness noted earlier.

The increase in rest recommendations in the timeframe of one-year since last defoliation (Figure 6 compared to Figure 5a) is a result of a new constraint we imposed against use of burn or burn/graze combinations if a unit had not been rested in the previous year. This change was operationally necessary for mixed-grass units, based on cooperator feedback, to ensure sufficient fuel exists on the unit to complete a prescribed fire following a prior-year defoliation.

We first issued guidance under the revised framework in 2020; the guidance was based on a single new annual updating cycle that began with the 2019–2020 paired data (Figure 4). In updates since the revision, Model 1 lost weight for both the mixed-grass and tallgrass competing model sets. In the mixed-grass prairies, support for Models 2, 3, and 4 increased at the expense of Model 1. In tallgrass prairies, support for Models 2, 3, 5, and 6 increased at the expense of Model 1, while support for Model 4 remained relatively unchanged. The shift in support away from Model 1 based on empirically derived parameters is corroborated by a recent retrospective analysis of the full set of NPAM data, which showed that treatment effectiveness varies substantially depending on the dominant invader (i.e., *P. pratensis* or *B. inermis*) and defoliation history (J.J. Gannon, U.S. Fish and Wildlife Service, unpub. data).

Assessing Progress Towards the NPAM Objective

The decision framework is designed around meeting the objective to increase the cover of native grasses and forbs at least cost. This objective is quantified in the decision framework as the utility function. The optimization procedure of the decision framework identifies a "best management action" to implement in the upcoming cycle, given the current vegetation and defoliation history state of a unit and our current understanding of how prairie vegetation responds to management. Management actions are identified that maximize utility values over time, thereby achieving the objective.

Beyond the technical aspects of "utility" in the decision framework, cooperators are interested in what constitutes "success" in terms of prairie restoration. Optimistically, managers hope for dramatic increases in the proportion of native grasses and forbs (corresponding to decreases in *P. pratensis* and *B. inermis*) as grazing and burning expand in scope and frequency under recommendations provided by NPAM decision support. Because actions under NPAM are a significant departure from decades of rest-dominated management, we hope that Service-owned prairies might

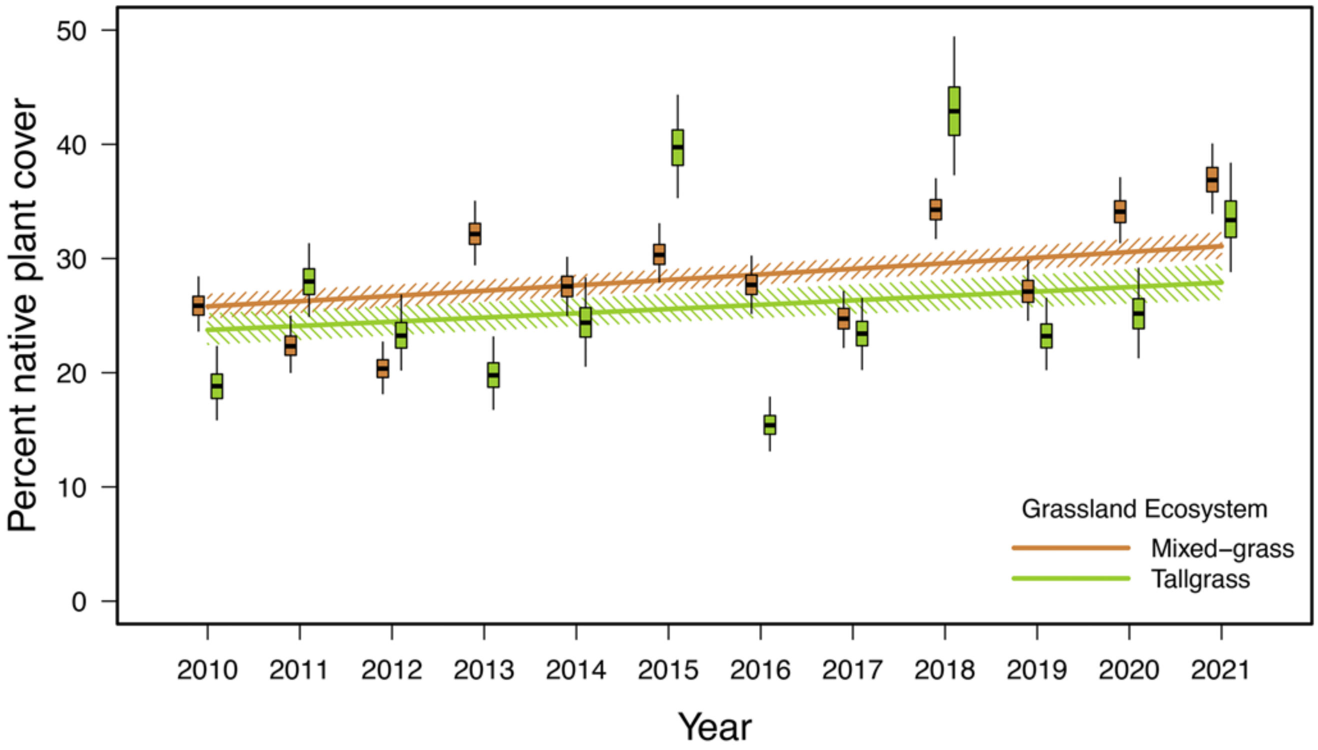

Figure 7. Percent cover of native grasses and forbs for NPAM units during 2010–2021. Trend lines of both mixed-grass and tallgrass prairies show an approximate two percent increase in native plant cover over this period (adapted from Moore et al. 2020).

respond quickly to actions that more closely resembled historical forces that shaped prairies (Grant et al. 2020a, 2020b). However, inventory results derived during Phase I document that many Service-owned prairies are substantially degraded by invasive plants. Because invasion pressures remain high and/or ecological thresholds of invasion may already have been crossed (Bestelmeyer 2006), restoration of degraded NPAM units may be unlikely or incredibly slow to accomplish. Under this scenario, success under NPAM might constitute maintenance of native plant assemblages at current levels, or even allow for slow but arrested declines over time relative to non-NPAM enrolled prairies that continue to degrade more rapidly (e.g., DeKeyser et al. 2009). Although we lack comparative time-interval data on non-NPAM units, we have seen that native plant composition has increased by about 2% during 2010–2021 for both mixed-grass and tallgrass NPAM prairies, suggesting our broad NPAM objective is realistic (Figure 7, adapted from Moore et al. 2020).

Additional Learning Facilitated by the NPAM Framework

NPAM was designed to address specific questions embodied by mixed-grass and tallgrass competing models. Beyond this focus, the standardized data collection and centralized data storage of NPAM provide opportunities to address other questions of interest to prairie managers and researchers. Adjunct projects are primarily of two types: 1) retrospective analyses conducted by the NPAM team and 2) collaborations with partners conducting research completely or partially on NPAM units (Supplementary Material, Table S4). Since program inception, there has been interest by the Service to support broader scientific investigations on prairies enrolled in NPAM. Some efforts address questions specific to elements of NPAM, while others use the structured management and monitoring tenets of NPAM to facilitate research on wildlife species. As NPAM gains support in the scientific community, we expect continued opportunities for adjunct research, using NPAM management and monitoring in concert with applied research to increase our understanding of prairie ecology in the northern Great Plains.

Conclusions

Lessons Learned and Moving Forward

Degradation of prairies has occurred over decades. Gaining understanding regarding the effects of this degradation requires a long-term multifaceted approach; one that is sensitive to forces that continue to disfavor native plant and animal species at an alarming rate. Inventory of Service-owned prairies and implementation of NPAM are complementary scientific endeavors. Inventories provide a snapshot in time of the current state of prairies across a broad continuum of ecological sites and climates. Results are especially useful for identifying primary uncertainties implicated in loss of native plant cover (e.g., hypotheses represented in NPAM models) and for categorizing and prioritizing prairie units for restoration. NPAM, in contrast, is a long-term endeavor for increasing native plant cover while augmenting our understanding of the effects of restorative management actions.

The challenge of implementing an adaptive management program of the scope and scale of NPAM cannot be overstated. NPAM, however, has proven a capable delivery mechanism both for prairie restoration and scientific understanding. State-based decision making within an adaptive management framework based on real-time learning is a vast departure from traditional approaches used by the Service to address ecological uncertainty. Traditional approaches can have catastrophic limitations as evidenced by the failure of the Service to capture the changing state of prairies held in public trust over many decades (Grant et al. 2009). For example, short-term, time-defined research projects (often by graduate students and independent researchers) require that managers wait for relevant findings to become available and then interpret the findings for their specific management implications (McNie 2007, Bisbal and Eaton 2023). Additionally, short-term efforts may fail to capture temporal influences of changing climate, annual variations in weather, and synergistic effects of multiple management actions implemented over time. In contrast, long-term monitoring projects may be designed to better capture temporal dynamic events, but are inconsistently applied, often with unclear or shifting objectives, resulting in poor success (Nichols and Williams 2006). Both approaches often lack replication across broad spatial landscapes, primarily because they are funded and applied within a specific refuge or other administrative unit without coordination among adjacent complexes that may share similar ecological issues. For decades, both short- and long-term projects relied on traditional hypothesis testing and statistical modeling that was susceptible to Type 1 and 2 errors, mainly because of small sample sizes and wide temporal and spatial variances. NPAM circumvents many of these limitations using a decision support adaptive management framework that was adopted across broad spatial and temporal gradients and enabled immediate and coordinated pursuit of management towards a common conservation objective. The NPAM framework facilitates consistent collection of well-replicated, long-term information necessary to achieve formal learning to improve prairie management.

McFadden et al. (2011) distinguished two schools of thought regarding approaches to adaptive management: the Resilience-Experimentalist School and the Decision-Theoretic School. Projects aimed at restoration often appear to fall into the former category, tending to be large projects organized around stakeholder involvement, experimentation, and complex ecological models (e.g., Ebberts et al. 2018, Noe et al. 2019, Beheshti et al. 2023). In contrast, NPAM belongs to the Decision-Theoretic School, in which progress towards a stated objective formally feeds back into a decision-making model with explicitly formulated uncertainties. Therefore, NPAM contains a structure that uses acquired monitoring data to regularly update the predictive models on which decisions are based, setting this program apart from many others.

Under NPAM, the choice of a best action each year does not change simply because conditions on the ground have changed: incremental change in understanding how the system responds to an action also drives the choice of action. In our view, "learning by doing" is best facilitated by a structure that includes a way to predict outcomes of actions under different hypotheses of system response, a systematic means of collecting data relevant to those hypotheses, and a formal mechanism to regularly update belief in the hypotheses. Applications that apply these principles in other natural resource contexts include the adaptive management of North American waterfowl (Nichols et al. 2007), the adaptive management of *Limulus polyphemus* (horseshoe crab) in Delaware Bay (McGowan et al. 2015), and the adaptive management of invasive *Phragmites australis* (common reed) in the Great Lakes Basin (Great Lakes Commission 2023).

NPAM has been operational for more than a decade and continues to have enthusiastic support of participants and Service leadership. This support stems from multi-partner collaboration, practical and informative decision framework components, and a sustained commitment to the process (Moore et al. 2011). Furthermore, NPAM was initiated, driven, and governed from the bottom-up: field staff (as opposed to administrators) identified the threat, defined the objective, and articulated the need for science-driven state-based management. Managers and biologists understand that NPAM is a long-term commitment; ecological improvements and learning within an adaptive management framework require commitment at least commensurate with the decades of degradation that resulted in the current state of decline. NPAM was built around existing management practices and capabilities, recognizing logistical and operational constraints in applying management actions and monitoring (in contrast to a research experiment with rigid requirements). The framework ensures standardization while preserving the manager's decision-making flexibility. Cooperators receive annual, site-specific management guidance and feedback, which is used in planning and implementation of management actions. NPAM has a formal infrastructure that includes a governing body, documented protocols, a centralized database, and automated data processing. These elements help ensure that NPAM is integrated into routine Service operations, thereby maintaining buy-in from the field and earned support from leadership.

The success of NPAM can be replicated as a vehicle for addressing ecological issues other than prairie restoration, with the proper investment of resources. Beyond resources necessary for development previously described in *The NPAM Setup Stage*, NPAM requires ongoing support for operational and technical needs. Dedicated personnel, including a program coordinator, database manager, and quantitative ecologist, provide the organization, communications, and technical expertise to administer NPAM (note that NPAM is a part-time component for individuals responsible for these tasks). These individuals are supported by an advisory team composed of several NPAM cooperators and USGS scientists who meet at least semi-annually. The advisory team is a permanent entity, providing continuity over time regardless of changes in individuals that comprise the team (e.g., retirement, relocation, etc.). Annual operations include training sessions (e.g., monitoring and data entry protocols), informational webinars, data processing, and generation of management recommendations. Periodic responsibilities that may occur over the years include updating protocol documentation, offering educational webinars or contributing to conferences, analyzing data retrospectively and communicating results to cooperators, and continuously assessing the fit of existing NPAM framework components for meeting cooperator needs.

We continue to pursue improvements to the decision framework while also addressing information gaps using retrospective analyses and partner research. Currently, we are exploring options to apply decision guidance at a broader scale (i.e., beyond units enrolled in NPAM) to increase native plant cover and encourage science-based decision-making. We are also analyzing NPAM data to address several smaller scale questions such as the timing of management treatments. Additionally, we have collaborated with research partners (e.g., USGS and universities) to address specific questions of interest to the Service and other prairie managers. Incorporation of additional learning (Supplementary Material, Table S4) continues to increase overall knowledge of prairie ecology and management. The Service will continue to apply NPAM to address fundamental hypotheses about prairie management and the role of invasive species in degradation of prairies. We expect these results to be informative to all managers and biologists tasked with prairie restoration. Finally, we hope that the NPAM developmental process will be of interest for addressing ecological issues that compromise systems other than prairies of the northern Great Plains.

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