Forum

Applying Ecologically Based Invasive-Plant Management

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Abstract

The need for a unified mechanistic ecological framework that improves our ability to make decisions, predicts vegetation change, guides the implementation of restoration, and fosters learning is substantial and unmet. It is becoming increasingly clear that integrating various types of ecological models into an overall framework has great promise for assisting decision making in invasive-plant management and restoration. Overcoming barriers to adoption of ecologically based invasive-plant management will require developing principles and integrating them into a useful format so land managers can easily understand the linkages among ecological processes, vegetation dynamics, management practices, and assessment. We have amended a generally accepted and well-tested successional management framework into a comprehensive decision tool for ecologically based invasive-plant management (EBIPM) by 1) using the Rangeland Health Assessment to identify ecological processes in need of repair, 2) amending our framework to include principles for repairing ecological processes that direct vegetation dynamics, and 3) incorporating adaptive management procedures to foster the acquisition of new information during management. This decision tool provides a step-by-step planning process that integrates assessment and adaptive management with process-based principles to provide management guidance. In our case-study example, EBIPM increased the chance of restoration success by 66% over traditionally applied integrated weed management in an invasive-plant–dominated ephemeral wetland ecosystem. We believe that this framework provides the basis for EBIPM and will enhance our ability to design and implement sustainable invasive-plant management and restoration programs.

Resumen

Existe una necesidad sustancial e insatisfecha de un marco ecológico unificado y mecanístico que mejore nuestra habilidad para tomar decisiones y predecir cambios en la vegetación, que guie la implementación de acciones de restauración, y que promueva el aprendizaje. Resulta cada vez más claro que la integración de varios tipos de modelos ecológicos dentro de un macro general tiene un futuro promisorio en la toma de decisiones para el manejo y la restauración de áreas afectadas por plantas invasoras. La superación de las barreras que obstaculizan la adopción de pautas de manejo ecológicas de plantas invasoras requerirá el desarrollo de principios cuya integración en un formato útil permitirá a los decisores entender fácilmente las conexiones entre procesos ecológicos, la dinámica de la vegetación, las prácticas de manejo y la evaluación. Hemos actualizado un marco de manejo de sucesión ampliamente aceptado y corroborado y lo hemos transformado en una herramienta exhaustiva para el Manejo Ecológico de Plantas Invasoras (EBIPM) mediante 1) el uso de la Evaluación del Estado de Salud del Pastizal para identificar procesos ecológicos que requieren reparación, 2) la inclusión de principios para reparar procesos ecológicos que dirigen la dinámica de la vegetación, y 3) la incorporación de procedimientos de manejo adaptativo para promover la adquisición de nueva información durante el proceso de manejo. Esta herramienta para la toma de decisiones detalla el proceso de planificación paso a paso e integra la evaluación y el manejo adaptativo con principios basados en procesos para proveer un guía de manejo. En el estudio de caso que utilizamos como ejemplo, el EBIPM aumentó las chances de éxito de restauración en un 66% sobre el manejo integral tradicional de un ecosistema de humedal efímero dominado por una planta invasora. Creemos que este marco provee la base para el EBIPM y mejorará nuestra habilidad de diseñar e implementar programas sustentables de manejo y restauración de áreas afectadas por plantas invasoras.

Key Words: adaptive management, augmentative restoration, decision tool, invasive plant, management framework, plant succession

INTRODUCTION

A major constraint in restoration ecology and invasive-plant management is the lack of a useful decision-making process with an ecological basis that allows prediction of vegetation dynamics in response to management (Halle and Fattorini 2004). It would be best in a format that improves land management decisions and fosters learning and transfer of knowledge from one situation to another. Historically, Clements (1916, 1936) provided a long-standing general theory that has been the basis for making decisions based on the paradigm that plant communities change linearly toward some climatically determined end point. Rangeland managers widely adopted this notion to condition class habitats based on the degree to which the plant composition deviated from that

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endpoint (Dyksterhuis 1949). As rangeland condition trended downward over time, managers adjusted animal stocking rates in an attempt to reverse the trend. Although this successional model was useful for several decades, it could not predict nonlinear dynamics and was more observational rather than linked to mechanistic ecology (Westoby et al. 1989). Increasingly severe and frequent disturbance regimes, global climate change, and invasion by nonindigenous plants have created a critical need for ecologically based land management that addresses the underlying cause of vegetation dynamics (Mclendon and Redente 1992; Sheley et al. 1996; Bradley et al. 2010). The need for a unified mechanistic ecological framework to improve land management decision-making abilities, predict vegetation change, and guide the implementation of restoration is substantial and unmet (Westoby et al. 1989; Bestelmeyer et al. 2003; Crain et al. 2005; Miller et al. 2005; Harpole 2006). Three primary portions of decision making include assessment, prediction of future vegetation change with and without imposed management, and evaluation. Vegetative characteristics have dominated most assessment systems on rangeland. These assessments have primarily focused on collecting data to help quantify the condition and trend of vegetation (Dyksterhuis 1949). Species composition and abundance numbers are compared to estimated pre–European settlement vegetation to suggest an ecological status, and are then compared over time (Daubenmire 1968). Recognition of the need to assess the condition of various ecosystem attributes to determine overall rangeland health has emerged, and is currently being adopted by many federal agencies (Pyke et al. 2002).

Accurate prediction of future vegetation dynamics in response to management has been elusive. Most theories and models aimed at predicting vegetation dynamics are of three types: 1) based on a very general ecological mechanism(s) that does not provide enough specific detail to guide management (Connell and Slatyer 1977; Grime 1977; Davis et al. 2000); 2) based on a specific mechanistic process that applies to populations, but not entire plant communities (Tilman 1980; Wedin and Tilman 1993; Fargione and Tilman 2005); or 3) not based on an ecological theory, but relies on prior knowledge and observation (Westoby et al. 1989; Laycock 1991). Arguments substantiating each model's value for use by managers to improve decisions are compelling. It is becoming increasingly clear that integrating various types of ecological models into an overall framework has great promise for assisting the decision making in invasive-plant management and restoration (Krueger-Mangold et al. 2006). Models linking specific mechanisms directing succession dynamics to a larger process-based framework with application across heterogeneous environments to predict multistate vegetation dynamics appear most useful (Sheley et al. 2006, 2009). However, these models have not been adopted by land managers with much more enthusiasm than less-robust model types. Adoption has been limited by model complexity, lack of scientific knowledge regarding how various mechanisms and processes contribute to vegetation dynamics, and absence of a holistic and intuitive model application process.

To create less complex and more useful models, our understanding of the mechanisms and processes directing plant community change must be complete enough to create ecological principles on which managers can base their decisions (James et al. 2010). Ecological principles are synthesized from the body of scientific knowledge about the ecological processes directing successional dynamics. In this form, the knowledge is framed in a manner useful to managers. When this occurs, managers can consider multiple ecological mechanisms and processes simultaneously, which is critical because a suite of complex factors generally interact to create successional patterns, and multiple factors will need amending to direct positive plant community trajectories. Like most well-developed fields of study, ecological restoration and invasive-plant science must focus on providing ecological principles, which will emerge from recognition of patterns in vegetation change in response to process manipulations.

Overcoming the barriers to adoption of ecologically based frameworks will require that principles be developed and integrated into a useful process for making management decisions. When land managers can visualize and understand the linkages among assessment, ecological processes, vegetation dynamics, and management practices, they will be empowered to implement more effective ecologically based invasive-plant management (EBIPM). The objective of this manuscript is to synthesize major components of management decision-making into a logical series of steps that can be followed by managers desiring to implement EBIPM. To achieve this objective, we have amended a successional management framework (Sheley et al. 1996) to provide a comprehensive decision tool for EBIPM by 1) using the Rangeland Health Assessment (Pyke et al. 2002) to identify ecological processes in need of repair (Sheley et al., in press), 2) amending our framework to include principles for repairing ecological processes that direct vegetation dynamics (James et al. 2010), and 3) incorporating adaptive management procedures to foster the acquisition of new information during management (Reever-Morghan et al. 2006). We briefly review our successional management framework, present a more holistic and intuitive EBIPM decision-making framework, discuss each component of the EBIPM decision-making framework, and provide a case study as an example of the framework for designing EBIPM programs.

CURRENT FRAMEWORK

On landscapes degraded by invasive plants, repairing ecological processes is critical to correcting the cause of the invasion rather than continuously or periodically treating the symptoms (Sheley and Krueger-Mangold 2003). Successional management has been tested as a process-oriented framework for developing ecologically based invasive-plant management strategies on rangelands (Sheley et al. 1996; Sheley and Krueger-Mangold 2003; Sheley et al. 2006). Pickett et al. (1987) provided the theoretical basis for successional management by developing a hierarchical model that includes the general causes of succession, controlling ecological processes, and their modifying factors (Table 1). The three causes of succession, including site availability, relative species availability, and relative species performance must all be considered in developing an integrated land-management program (Luken 1990). Based on what is known of the conditions, mechanisms, and processes controlling plant community dynamics, the causes of succession can be modified to allow predictable

Table 1. Causes of succession, contributing processes, and modifying management factors (from Sheley and Krueger-Mangold 2003).

Causes of succession	Processes	Management factors
Site availability	Disturbance	Size, severity, time intervals, patchiness, predisturbance history
Species availability	Dispersal	Dispersal mechanisms and landscape features
	Propagule pool	Land use, disturbance interval, species life history
Species performance	Resource supply	Soil, topography, climate, site history, microbes, litter retention/decomposition
	Ecophysiology	Germination and establishment requirements, assimilation rates, growth rates, genetic differentiation
	Life history	Allocation, reproduction timing, and degree
	Stress	Climate, site history, prior occupants, herbivory, natural enemies
	Interference	Competition, hebivory, allelopathy, resource availability, predators, other level interactions

successional transitions toward desired plant communities (Sheley et al. 1996; Whisenant 1999; Bard et al. 2004).

Site availability is most often associated with the process of disturbance. Disturbance plays an important role in initiating and altering successional pathways by creating safe sites or open niches in ecosystems (Pickett and White 1985; Lozon and MacIsaac 1997). Disturbance reduces competitive intensity, modifies environmental conditions, and alters resource supply rates (Collins et al. 1985; Runkle 1985; Davis et al. 2000; Krueger-Mangold et al. 2006). Thus, altering disturbance regimes, and consequently, factors that favor germination, establishment, and growth of native species over invasive species may be a way to direct succession toward the desired plant community (D'Antonio and Meyerson 2002).

Species availability is largely determined by colonization. Colonization, the availability and establishment of various species, is another important process directing succession. Establishment of particular species is often explained by the presence or absence of viable seeds brought in by dispersal or present in the soil seedbank (Gross 1980; Gross and Werner 1982; Gross 1999; Bischoff 2002; Christen and Matlack 2009). For example, in rangeland dominated by spotted knapweed (*Centaurea bierbersteinii* DC), Sheley et al. (1999) increased intermediate wheatgrass (*Elytrigia intermedia* [Host] Neveski) establishment by increasing the amount of viable seeds available. When changes in seed availability alter plant densities of particular species, the competitive balance among populations can shift (Egler 1952; Parks et al. 2008; Wallin et al. 2008). In other words, manipulating availability and density of species can shift the competitive balance toward desired species (Velagala et al. 1997).

The relative ability of species to perform (species performance) in different environmental conditions also influences successional dynamics. Resource availability and the ability of populations to capture those resources (Tilman 1986), ecophysiological plant traits (Larcher 1995), stress and species' ability to avoid or tolerate stress (Grime 1977), and trade-offs associated with life-history strategies (Crawley 1997) influence the success or failure of a species. If extra resources become available (e.g., disturbance), invasive species will typically capitalize on them before native, desired species (Norton et al. 2007; Roundy et al. 2007; Dickson and Foster 2008). For example, the competitive ability of the invasive plant *Centaurea diffusa* L. is reduced proportionately more than native species in soils with low soil phosphorous availability relative to soils with high phosphorous availability (Suding et al. 2004). Thus, manipulating factors that influence the performance of species may be critical to promoting desired species.

The successional management model has been tested as a framework for restoration of invasive-plant–infested wildlands with promising success (Sheley et al. 2006). The hypothesis was accepted that as invasive-plant management increasingly addressed the factors that modify or repair the processes influencing the three general causes of succession in a complementary manner, the establishment and persistence of native desired species would increase (Sheley et al. 1996; Sheley et al. 2006). In fact, Sheley et al. (2009) used this conceptual framework to improve restoration approaches and successional management of heterogeneous wildland systems. In two of the three sites using augmentative restoration, a management strategy whereby damaged ecological processes are supplemented on a site-specific basis, land managers improved their decision as to the treatment combinations to maximize seedling establishment. Selectively augmenting processes that remain partially intact but are occurring at inadequate levels can improve restoration across heterogeneous landscapes. Besides the clear economic advantages of lower management inputs associated with augmentative restoration, avoiding unnecessary management inputs has the additional advantage of minimizing unintended negative impacts on ecosystem processes.

IMPROVED DECISION-SUPPORT FRAMEWORK

In the initial version of successional management, ecological processes were identified, but there were no examples of unifying principles that could be used to assist in making management decisions. Instead managers have been left to use their own experience and intuition to identify tools and approaches needed to repair and modify ecological processes successfully. The EBIPM process recognizes that managers' knowledge and experiences on their sites are important to consider in management planning; however, by providing an ecological basis for their management decisions, more effective solutions to invasive species can be identified. As a way to overcome the adoption barriers associated with the successional management framework, we created a step-by-step holistic process managers can use to design, implement, and test science-based solutions to land management problems (Fig. 1). This model incorporates a successional dynamics framework that provides a guide to addressing the ecological causes of

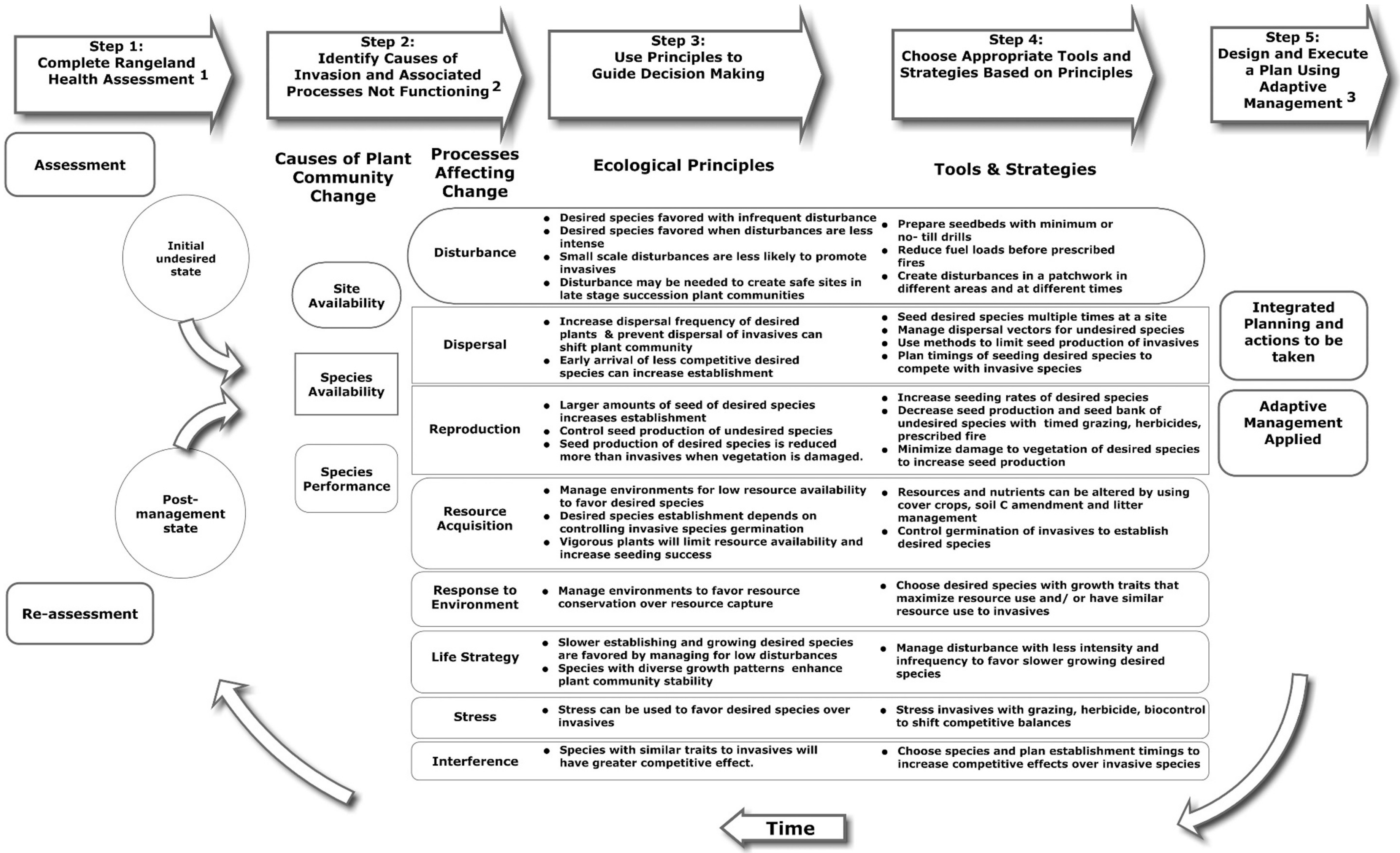

Figure 1. Revised ecologically based invasive-plant management successional model/framework describing rangeland assessment, causes of succession, processes influencing these causes, planning and management guidelines, and adaptive management (Reever-Morghan et al. 2006; James et al. 2010; Sheley et al., in press).

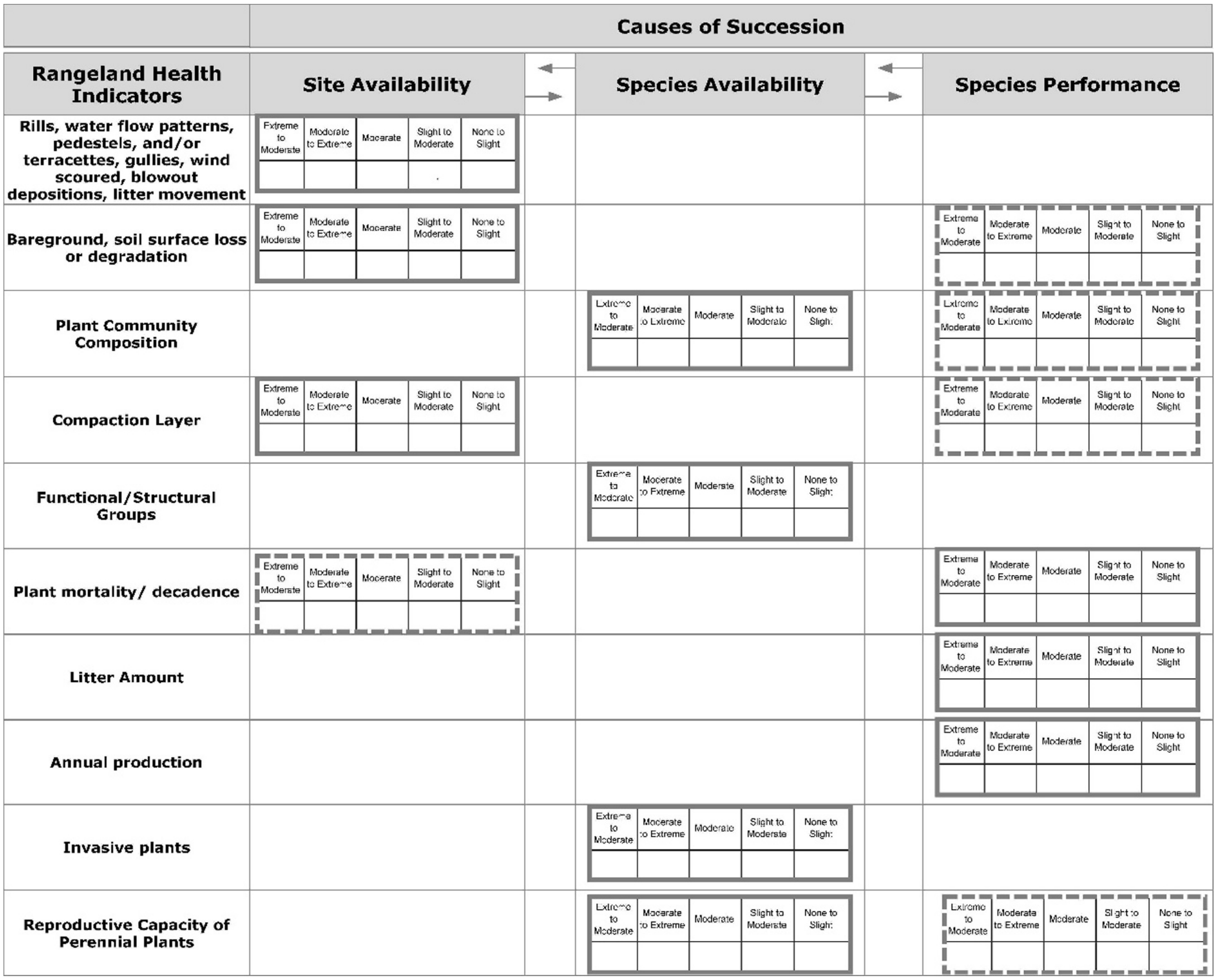

Figure 2. Summary worksheet adapted from Rangeland Health Assessment indicators rating the primary (solid box) and secondary (dashed-box) causes of succession. Several of the 17 indicators have been categorically combined for use with the ecologically based invasive-plant management framework. The ratings are made comparing the deviation from the ecological site description.

succession, retrogression, and invasion (Sheley et al. 2006). The model integrates assessment and adaptive management with process-based principles to guide managers to apply tools and techniques successfully in the design and implementation of effective EBIPM programs.

In the following section we provide a detailed description of the EBIPM steps along with case study examples of how the steps can be applied. The case study was conducted to test the EBIPM decision-making model (Sheley et al. 2009). In the study example, our overall goal was to restore native plant communities to pre-European settlement conditions with respect to ecosystem organization, structure, and function. Three distinct study sites were chosen in order to identify and to repair or replace damaged processes selectively, based on their influence on the causes of succession. Once the damaged processes were repaired, we anticipated that invasive plant species would become a subordinate portion of the system (Pokorny et al. 2005).

Step 1: Complete Rangeland Health Assessment

Most rangeland assessment protocols are aimed at providing information needed to evaluate current condition and past trend. Currently, the Rangeland Health Assessment is the primary method being adopted, and is in the process of being implemented throughout most government agencies (Pellant et al. 2005). This method is intended to provide preliminary evaluation of rangelands at the ecological site level. A completed Rangeland Health Assessment provides valuable information for indicating current rangeland conditions.

Assessment information can help identify ecological processes currently in disrepair, which are likely responsible for directing successional patterns away from native plants. In an effort to provide an accurate assessment of a given ecological site and to avoid another layer of assessment for rangeland managers to conduct, we developed a method to use the Rangeland Health Assessment approach by including specific details related to the causes of succession, process state, and ranking system (Sheley et al., in press; Fig. 2). With the addition of this worksheet, the assessment not only provides evaluation criteria, but now provides information needed to make improved decisions about repairing or replacing ecological processes during management. In addition to assessing the condition and trends of ecosystems, the assessment can be used to collect data critical to making appropriate ecologically based decisions.

Evaluators completing the Rangeland Health Assessment rate a site with the use of categories that describe a gradient for each indicator associated with attributes of an ecosystem's status. In this assessment, 17 indicators have been identified for evaluation. The indicators are components of an ecosystem that can be evaluated. In the worksheet developed for EBIPM, several indicators were categorically grouped and a designation was made if they primarily or secondarily affected the three causes of succession. Ratings are made in a range from 1 to 5 based on the indicators' deviation from expected conditions, extreme (5) being the farthest from expected, and none to slight (1) being the closest to the expected for that ecological site (Pyke et al. 2002). The further deviation from expected, the more likely the processes associated with the indicator variable need repaired or replaced. By completing Step 1 and assessing an ecological site in this way, a manager gains concrete and verifiable information to directly identify the most important causes of succession and an indication of those processes that are not functioning properly.

Case Studies. To initiate the EBIPM process, the case-study sites were assessed with the use of the Rangeland Health Assessment protocol. Resulting data were entered into the EBIPM worksheet (Fig. 2). The sites were in a heterogeneous ephemeral wetland dominated by invasive plants (spotted knapweed; sulphur cinquefoil, *Potentilla recta* L.; cheatgrass, *Bromus tectorum* L.). Site 1 had substantial meadow vole (*Microtis pennsylvanicus*) disturbance that increased bare ground and thus site availability as determined from the worksheet indicator "bareground and soil surface loss." In addition, this site had xeric soils with a low remnant stand of native functional groups relative to the ecological site description. Low-remnant desired species suggested species availability was low as the worksheet indicators "plant community composition," "functional/structural groups," and "invasive species" were found to deviate extreme to moderate from the ecological site description.

In contrast, Site 2 had low meadow vole disturbance with minimal site availability. A relatively large remnant stand of native functional groups remained; however, there were areas dominated by invasive species. The worksheet indicator for species availability, "reproductive capacity of perennial plants," denoted minimal deviation from the site description. But, invasive plants were evident and seed production would need to be limited, and also species performance of desired species would need to be addressed for successful restoration efforts.

The third site was located adjacent to a wetland with high soil moisture (mesic) favorable to desired species. Indicators from the worksheet confirmed minimal deviation from the site description for species performance of desired species. But with few safe sites, site availability deviated extreme to moderate on the worksheet indicators. Addressing species availability at Site 3 emerged as one priority from the assessment worksheet as "plant community composition," "functional/structural groups," and "invasive plants" all indicated extreme to moderate deviation from the ecological site description.

Step 2: Identify Causes of Invasion and Associated Processes

The basis of this improved model uses the same successional management framework as in previous descriptions (Sheley et al. 1996; Sheley and Krueger-Mangold 2003; Sheley et al. 2006). In this step, managers use the assessment information to identify the primary cause or causes of succession that appear to be favoring dominance by invasive plants. By using a worksheet developed from the Rangeland Health Assessment, a manager can consider the specific processes and degree to which the processes may be acting on the causes (Fig. 2). Multiple processes may be impacting any of these three causes of succession. Because altering the "cause" of invasion is central to EBIPM, the aim is to alter the key processes in a particular ecological site to influence each "cause of succession" to direct vegetation dynamics on a desired trajectory. Ultimately, being able to identify the ecological processes acting on the causes of succession allows land managers to choose strategies and tools to alter processes in need of repair to address the underlying cause of invasion (Sheley et al. 2009).

Case Studies. In Step 2, we used the assessment information to identify ecological processes associated with each successional "cause" in disrepair. Because Site 1 was found to have a high level of bare ground as a result of disturbance by meadow voles, site availability was adequate for establishment of desirable species. On the other hand, desired species availability and soil moisture (species performance) were insufficient for seedling establishment. At Site 2, lack of disturbance appeared to limit safe sites for desired species because the remnant stand of desired species was over 20% intact and likely produced desired species propagules to reoccupy the site once invasive species were controlled with the use of herbicides (altering relative species performance).

At the wettest portion of the area (Site 3), species performance involving the processes for seed imbibition and plant growth appeared adequate for desired species and the wet areas were too wet for the invasive species to dominate. However, disturbance processes were inadequate to create safe sites (site availability) and desired species propagules were apparently absent (species availability).

Step 3: Use Principles to Guide Decision Making

Ecological principles were developed and linked to processes to guide management planning and decision making (Fig. 1). Ecological principles have been synthesized from existing scientific literature to provide direction for management (James et al. 2010). In restoration ecology, ecological principles have been slow to emerge, likely due to the complexity of ecosystems and because it is a relatively new science. With the development of ecological principles, managers have a stronger, science-based foundation from which to make informed land-management decisions. Each ecological principle provides an ecological objective or target managers might try to attain to direct plant community trajectory toward a more desired state (Fig. 1). Achieving that specific objective would most likely repair a process to stimulate favorable vegetation dynamics. There may be more than one principle for any process, and there are likely multiple processes to consider for each of the three causes of succession used in this framework. The benefit of this step is that it synthesizes knowledge into a useful series of principles that can be used to choose tools and strategies during management decision making. These ecological principles provide the basis on which managers can evaluate the potential usefulness of techniques and tools during the planning processes.

Case Studies. On Site 1, we adopted the principles associated with species availability to "increase dispersal frequency of desired species" and species performance to "manage environments to favor germination and establishment of desired species" because too few desired species remained to colonize the area. The main constraint at Site 2 was that safe sites were lacking for desired species germination, establishment, and growth. The ecological principle associated with site availability to guide management choices at Site 2 was "desired species will be favored when disturbances are less frequent and less intense." The species performance principle that applied at Site 2 related to stressing the invasive plants "to favor desired species over invasive species." At Site 3 all principles associated with site availability and species availability were considered; however, the principle "desired species will be favored when disturbances are less frequent and less intense" guided the main strategy chosen. Additionally, a principle for species performance "desired species with similar traits to invasive species will have greater competitive effect" further refined management decisions.

Step 4. Choose Appropriate Tools and Strategies Based on Principles

There is a critical link between the ecological processes in disrepair and the choice of management tools and strategies. Ecological principles provide rules of thumb and ecological objectives that will most likely facilitate a desired change in vegetation dynamics. Tools and strategies can be chosen by determining the likelihood that a certain technique will achieve the ecological objective provided by the associated principle. This will allow some rudimentary prediction of the direction of change that a strategy will provoke in vegetation dynamics. In Figure 1, each process is associated with a corresponding principle, and each principle is associated with a corresponding management action. To the extent the direction and magnitude a tool influences ecological process is known, managers can choose among and integrate them based on the identified processes in need of repair and their associated principles.

Case Studies. At Site 1, the processes in disrepair were likely associated with dispersal of desired species and ecophysicological barriers to germination and emergence, especially lack of water. When resources are limited, as in the case with soil moisture at Site 1, the strategy adopted included seeding with desirable species (adding propagules to a system not producing adequate amounts), with the use of a rangeland drill with depth bands and temporary irrigation to stimulate germination and emergence of desired species. At Site 2, because there was adequate remnant native stand, species availability of the native stand was addressed through promoting natural seedling establishment by lightly disking and imprinting the soil surface to collect moisture and providing temporary irrigation to stimulate germination and emergence of desired species. However, invasive seed production needed to be limited and the plants stressed to give a competitive advantage to the desired species. The best management tool to address these processes for Site 2 was to make an herbicide application to create the needed level of stress on the invasive species. At Site 3, there was not adequate site availability. Lightly disking the site to create a less-intense disturbance for opening up safe sites was the chosen strategy. We were guided to seed this site with a diverse group of native species with traits useful to exploiting high moisture conditions to address the species-performance processes related to plant interference.

Step 5: Design and Test the Program With the Use of Adaptive Management

Ecologically based invasive-plant management provides a science-based method for developing management plans and predicting the outcome. However, the true effectiveness of imposed management will have substantial uncertainty. Adaptive management is a way for managers to operate in the face of uncertainty and learn by doing, which involves using actual management to test different management alternatives and expand our knowledge about a system (Reever-Morghan et al. 2006). Managers gain greater knowledge of their system by testing management alternatives during the management process. Adaptive management has numerous permutations. There continues to be confusion about its definition and use (Dewey and Andersen 2004; Reever-Morghan et al. 2006). Even though guidelines are beginning to emerge, managers lack sufficiently clear information for implementation. Regardless, the process of adaptive management is ideally suited as part of EBIPM, once management questions are formulated. One strength of adaptive management is that managers are able to manage in the face of uncertainty and learn by doing by using some basic principles of experimental design (Reever-Morghan et al. 2006).

Thoughtfully choosing response variables that best tell whether the system is moving towards management objectives will make the resulting data analysis more helpful to inform the next management decision-making period. It is valuable to start with a simple adaptive-management experiment testing only a few alternatives against control plot with replications. Including researchers in the management process so they can lend their expertise in the ecology of the system, the development of the experimental design, and the analysis of the resulting data is also of value. Incorporating adaptive-management data as part of EBIPM evaluation results in stronger knowledge of the system, confidence that the management strategy developed in the process is the best alternative for the site, and a management program that is scientifically valid and easy to defend. Increased use of adaptive management will enhance our ability to improve decision making over time.

Case Studies. In our case-study sites, we applied various combinations of light disking, seeding, and supplemental watering based on the initial conditions of the specific area within the management unit. These tools and techniques were chosen because of their perceived ability to favorably alter the ecological processes as suggested by the associated principles. The application of these techniques was applied and tested with the use of the adaptive-management framework (Reever-Morghan et al. 2006; Sheley et al. 2009). It included seeding replication and controls, as well as alternative management techniques. Shallow tilling, watering, and seeding were applied in a factorial arrangement at all three sites. These eight treatment combinations were applied in a split-plot design with four replications to generate 32 whole plots (2 m^2). An application of 2,4-D was made on half of each whole plot to influence relative species performance. In two of the three sites (66%) decision making based on the EBIPM process improved the final outcomes by maximizing seedling establishment. By addressing ecological processes in disrepair, invasive-plant infestations were more effectively managed. Overall, this enhanced successful restoration percentages.

MANAGEMENT IMPLICATIONS

Enduring invasive-plant management and ecosystem restoration can only be achieved if the underlying ecological cause of invasion is altered to favor successional dynamics toward a desired plant community, and ultimately, their associated interactions with other essential components of the ecosystem. Improvement in our ability to implement EBIPM has been enhanced through the development of a decision-making tool that links assessment, ecological processes, management, and learning during management. The stepwise process outlined in this article gives managers a clearer decision-making process for ecosystem management. In the first step, a manager completes a Rangeland Health Assessment. In the second step the assessment information is used to determine the causes of succession in disrepair and the ecological processes that may be negatively impacting the causes. This step helps a manager elucidate the true causes of invasive-plant infestations. Ecological principles that link the processes to tools and strategies have been developed and included as Step 3. The principles link the processes to general rules of thumb to help guide the choice of tools and strategies and predict the outcome of their use. Step 4 builds from the principles by supporting managers in choosing and integrating tools to best address repairing processes. In the fifth and final step, land managers use adaptive management to form and set up a management plan. Adaptive management plans should include a control, landscape scale replication and a monitoring schedule so managers can learn how the plan is working. Adaptive management, as part of the overall EBIPM process, provides the feedback mechanism for adjusting, as knowledge is gained from earlier management applications. The more holistic nature of the improved ecologically based successional dynamics model provides the thought process and direction to apply tools and techniques across landscapes to influence ecological processes to shift vegetation dynamics in a favorable direction. We believe this holistic decision framework provides the basis for EBIPM and will enhance ability to design and implement sustainable invasive-plant management and restoration programs.

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