

1 Running Head: Applying EBIPM

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5 **Applying Ecologically-based Invasive Plant Management**

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13 The need for a unified mechanistic ecological framework that improves our ability to make

14 decisions, predict vegetation change, guides the implementation of restoration, and fosters

15 learning is substantial and unmet. It is becoming increasingly clear that integrating various types of

16 ecological models into an overall framework has great promise for assisting the decision-making

17 in invasive plant management and restoration. Overcoming the barriers to adoption of

18 ecologically-based invasive plant management will require that principles be developed and

19 integrated into a useful format so land managers can easily understand the linkages among

20 ecological processes, vegetation dynamics, management practices, and assessment. We have

21 amended a generally accepted and well-tested successional management framework to provide a

22 comprehensive decision-tool for EBIPM by 1) using the Rangeland Health Assessment to

23 identify ecological processes in need of repair, 2) amending our framework to include principles

24 for repairing ecological processes that direct vegetation dynamics, and 3) incorporating adaptive
25 management procedures to foster the acquisition of new information during management. This
26 model integrates assessment and adaptive management with process-based principles that
27 provide the direction to successfully apply tools and techniques. In our study example, EBIPM
28 increased the chance of restoration success by 66 percent over traditionally applied integrated
29 weed management in an invasive plant dominate ephemeral wetland ecosystem. We believe that
30 this framework provides the basis for EBIPM and will enhance our ability to design and
31 implement sustainable invasive plant management and restoration programs.

32 **Nomenclature:** cheatgrass, *Bromus tectorum* L. BROTE; spotted knapweed, *Centaurea*
33 *bierbersteinii* DC. CENMA; intermediate wheatgrass, *Elytrigia intermedia* (Host) Neveski
34 ELIN; *Centaurea diffusa* Lam, CENDE; sulphur cinquefoil, *Potentilla recta* L. PTLRC; meadow
35 vole, *Microtis pennsylvanicus*.

36 **Key words:** Invasive plant; plant succession; augmentative restoration, adaptive management

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47 A major problem in restoration ecology and invasive plant management is the lack of a useful
48 decision-making process with an ecological basis that allows predictions of vegetation dynamics
49 in a format that improves land management decisions and fosters learning and transfer of
50 knowledge from one situation to another (Halle and Fattorini 2004). Historically, Clements
51 (1916, 1936) provided a long-standing general theory that provided the basis for making
52 decisions based on the paradigm that plant communities change linearly toward some
53 climatically determined endpoint. Rangeland managers widely adopted this notion to condition
54 class habitats based on the degree to which their plant composition deviated from that endpoint
55 (Dykerhaus 1949). As rangeland condition trended downward over time, managers adjusted
56 animal stocking rates in an attempt to reverse the trend. Although this successional model was
57 useful for several decades, it could not predict non-linear dynamics and was more observational
58 rather than linked to mechanistic ecology (Westoby et al. 1989). Increasingly severe and frequent
59 disturbance regimes, global climate change, and invasion by non-indigenous plants have created
60 a critical need for ecologically-based land management that addresses the underlying cause of
61 vegetation dynamics (Sheley et al. 1996). The need for a unified mechanistic ecological
62 framework that improves our ability to make decisions, predict vegetation change, guides the
63 implementation of restoration, and fosters learning is substantial and unmet (Westoby et al. 1989,
64 Bestelmeyer et al. 2003, Crain et al. 2005, Miller et al. 2005, Harpole 2006).

65 Three primary portions of decision-making include assessment, prediction of future vegetation
66 change with and without imposed management, and evaluation. Vegetative characteristics have
67 dominated most assessments systems on rangeland. These assessments have primarily focused
68 on collecting data that helps quantify the condition and trend of vegetation (Dyksterhaus 1949).
69 Species composition and abundance numbers are compared to estimated pre- European

70 settlement vegetation to suggest an ecological status and compared over time (Daubenmire
71 1968). Recognition of the need to assess the condition of various ecosystem attributes to
72 determine overall rangeland health has emerged and is currently being adopted by many Federal
73 agencies.

74 Accurate prediction of future vegetation dynamics in response to management has been
75 elusive. Most theories and models aimed at predicting vegetation dynamics are of three types: 1)
76 based on a very general ecological mechanism(s) that do not provide enough specific detail to
77 guide management (Grime 1977, Connell and Slatyer 1977, Davis et al. 2000), 2) based on a
78 specific mechanistic process that applies to populations, but not entire plant communities
79 (Tilman 1980, Wedin and Tilman 1993, Fargione and Tilman 2006), or 3) not based on a
80 ecological theory, but rely on prior knowledge and observation (Westoby et al. 1989, Laycock
81 1991).

82 Arguments substantiating each models value for use by managers to improve decisions are
83 compelling. It is becoming increasingly clear the integrating various types of ecological models
84 into an overall framework has great promise for assisting the decision-making in invasive plant
85 management and restoration (Krueger-Mangold et al. 2006). Models linking specific
86 mechanisms directing succession dynamics to a larger process-based framework that allows
87 application across heterogeneous environments to predict multi-state vegetation dynamics appear
88 most useful (Sheley et al. 2006, Sheley et al. 2009). However, these models have not been
89 adopted by land managers with much more enthusiasm than less robust model types. Adoption
90 has been limited by model complexity, lack of scientific knowledge regarding how various
91 mechanisms and processes contribute to vegetation dynamics, and lack of a holistic and intuitive
92 model application process.

93 To create less complex and more useful models, our understanding of the mechanism and
94 processes directing plant community change must be complete enough to create ecological
95 principles on which managers can base their decisions (James et al. IN REVIEW). Principles can
96 provide a synthesis of the scientific knowledge about the ecological processes that direct
97 dynamics in a manner that is useful to managers. When this occurs, managers can consider
98 multiple ecological mechanisms and processes simultaneously, which is critical because a suite
99 of complex factors generally interact to create successional patterns, and multiple factors will
100 need amending to direct positive plant community trajectories. Like most evolved fields of study,
101 ecological restoration and invasive plant science must focus on developing ecological principles,
102 which will emerge from recognition of patterns in vegetation change in response to process
103 manipulations.

104 Overcoming the barriers to adoption of ecologically-based frameworks will require that
105 principles be developed and integrated into a useful format so land managers can easily
106 understand the linkages among ecological processes, vegetation dynamics, management
107 practices, and assessment. We have amended a successional management framework (Sheley et
108 al. 1996) to provide a comprehensive decision-tool for EBIPM by 1) using the Rangeland Health
109 Assessment to identify ecological processes in need of repair, 2) amending our framework to
110 include principles for repairing ecological processes that direct vegetation dynamics, and 3)
111 incorporating adaptive management procedures to foster the acquisition of new information
112 during management. We briefly review our generally accepted and broadly tested framework,
113 present a more holistic and intuitive EBIPM decision-making framework, discuss each
114 component of the EBIPM decision-making framework, and provide direction for using the
115 improved framework for designing EBIPM programs.

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CURRENT FRAMEWORK

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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 include site availability, relative species availability, and relative species performance (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 successional transitions toward desired plant communities (Sheley et al. 1996, Whisenant 1999, Bard et al. 2003).

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 Maclsaac 1997). Disturbance reduces competitive intensity, modifies environmental conditions, and alters resource supply rates (Runkle 1985, Collins et al. 1985, Davis et al. 2000, Krueger-Mangold et al. 2006). Furthermore, litter and soil disturbance can potentially facilitate the movement of seed and establishment of distant individuals (Marshall and Buckley 2008). Thus, altering disturbance regimes, and consequently, factors that favor germination, establishment and growth of native

139 species over invasive may be a way to direct succession toward the desired plant community
140 (D'Antonio and Meyerson 2002).

141 Species availability is largely determined by colonization. Colonization, the availability and
142 establishment of various species, is another important process directing succession.

143 Establishment of particular species is often explained by the presence or absence of viable seeds
144 brought in by dispersal or present in the soil seedbank (Gross and Werner 1982, Gross 1980,
145 Gross 1999, Bischoff 2002, Christen and Matlack 2009). For example, in rangeland dominated
146 by spotted knapweed (*Centaurea biebersteinii* DC), Sheley et al. (1999) increased intermediate
147 wheatgrass (*Elytrigia intermedia* (Host) Neeski) establishment by increasing the amount of
148 viable seeds available. When changes in seed availability alter plant densities of particular
149 species, the competitive balance among populations can shift (Egler 1954, Parks et al. 2008,
150 Wallin et al. 2008). In other words, manipulating availability and density of species can shift the
151 competitive balance toward desired species (Velagala et al. 1997).

152 The relative ability of species to perform (species performance) in different environmental
153 conditions also influences successional dynamics. Resource availability and the ability of
154 populations to capture those resources (Tilman 1986), ecophysiological plant traits (Larcher
155 1995), stress and species ability to avoid or tolerate stress (Grime 1979), and trade-offs
156 associated with life history strategies (Crawley 1997) influences the success or failure of a
157 species. If extra resources become available (e.g. disturbance), weeds will typically capitalize on
158 them before native, desired species (Norton et al. 2007, Roundy et al. 2007, Dickson and Foster
159 2008). For example, the competitive ability of the invasive plant *Centaurea diffusa* L. is reduced
160 proportionately more than native species in soils with low soil phosphorous availability relative

161 to soils with high phosphorous availability (Suding et al. 2004). Thus, manipulating factors that
162 influence the performance of species may be critical to promoting desired species.

163 This model has been tested as a framework for restoration of invasive plant infested wildlands
164 with promising success (Sheley et al. 2006). The hypothesis that as invasive plant management
165 increasingly addressed the factors that modify or repair the processes influencing the three
166 general causes of succession—site availability, species availability, species performance—in a
167 complementary manner, the establishment and persistence of native desired species would
168 increase was accepted (Sheley et al. 1996, Sheley et al. 2006). In fact, Sheley et al. (2009) used
169 this conceptual framework to improve restoration approaches and successional management of
170 heterogeneous wildland systems. In 2 of the 3 sites, using augmentative restoration to guide
171 their management approaches improved their decision as to the treatment combinations that
172 would maximize seedling establishment. Selectively augmenting successional processes that
173 remain intact by repairing or replacing successional processes occurring at inadequate levels can
174 extend traditional successional management theory and provide a refined process-based theory
175 for restoration across heterogeneous landscapes. Besides the clear economic advantages of
176 lower management inputs associated with augmentative restoration, avoiding unnecessary
177 management inputs has the additional advantage of minimizing unintended negative impacts on
178 ecosystem processes.

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180 **IMPROVED DECISION-SUPPORT FRAMEWORK**

181 In the original framework, processes were identified but there was no attempt to provide
182 examples of unifying principles that could be used to make management decisions. Instead
183 managers were left to utilize their own experience and intuition to identify tools and approaches

184 needed to successfully repair and modify ecological processes. In order to overcome the
185 adoption barriers associated with ecologically-based frameworks, we created a more holistic
186 process that managers can use to design, implement and test science-based solutions to land
187 management problems (Figure 1). This model integrates assessment and adaptive management
188 with process-based principles that provide the direction to successfully apply tools and
189 techniques. Moreover, this model incorporates a successional dynamics framework that provides
190 a guide to addressing the causes of succession, retrogression, and invasion (Sheley et al. 2006).

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192 **Assessment**

193 Most rangeland assessment protocols are aimed at providing information needed to evaluate
194 current condition and past trend. Rangeland health assessments have been developed and are in
195 the process of being implemented throughout most government agencies (Pellant et al. 2005). A
196 major focus of assessment should also be to identify ecological processes currently in disrepair
197 that may be responsible for directing successional patterns in a negative direction. We suggest
198 enhancing the Rangeland Health Assessment approach (Pellant et al. 2005) by including specific
199 details related to the cause of succession, process state, and ranking system (Table 2). This
200 assessment would not only provide evaluation criteria, but also provide information needed to
201 make decisions about repairing or replacing ecological processes during management. In
202 addition to assessing the condition and trends of ecosystems, assessment can be used to collect
203 data critical to making appropriate ecologically-based decisions. The most significant link is
204 between the ecosystem indicator and its code. Codes range based on the deviation from expected
205 conditions. The further codes deviate from expected the more likely the processes associated
206 with the indicator variable need repaired or replaced.

207 **Causes and processes**

208 The core of the improved framework uses the same successional management model as in
209 previous descriptions (Sheley et al. 1996, Sheley and Krueger-Mangold 2003, Sheley et al.
210 2006). The three causes of succession include site availability, species availability, and relative
211 species performance (Luken 1990; Table 1). Ecologically-based invasive plant management is
212 aimed at altering the key processes in a particular ecosystem or situation to direct succession on a
213 desired trajectory. Management efforts use strategies and tools that alter the processes that are in
214 need of repair in an attempt to address the underlying cause of invasion (Sheley et al. 2009).

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216 **Process-based principles of management and the strategies and tools**

217 In this improved framework, principles are synthesized from existing scientific literature to
218 provide direction for management (James et al. IN REVIEW) (Table 3). Each ecological
219 principle provides an ecological objective that management might try to attain because scientific
220 data suggests that achieving that specific objective would most likely repair a process to
221 stimulate favorable vegetation dynamics. There may be more than one principle for any process,
222 and there are likely multiple processes to consider for each of the three causes of succession used
223 in this framework. The benefit of this method is that it synthesizes knowledge into a useful series
224 of principles that can be used to make management decisions. Another major benefit is that these
225 ecological principles provide the basis on which managers can evaluate and compare various
226 techniques and tools during the planning processes. This work also provides a state of the art
227 description of how the primary strategies and tools of invasive plant management can be used to
228 influence ecological processes in a positive way.

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230 **Adaptive Management**

231 Ecologically-based invasive plant management provides a science-based method for
232 developing management plans and predicting its outcome. However, the true effectiveness of
233 imposed management will have substantial uncertainty. Adaptive management is a way for
234 managers to operate in the face of uncertainty and learn by doing, which involves learning using
235 actual management to test different management alternatives and expand our knowledge about a
236 system (Reever-Morgan et al. 2006). Managers gain greater knowledge of their system by
237 testing management alternatives during the management process. There has been much talk
238 about adaptive management, but there is much confusion about exactly what it is (Dewey and
239 Andersen 2004, Reever-Morgan et al. 2006), and managers are hard-pressed to find any clear
240 guidelines for implementing it. The process of adaptive management involves formulating
241 management questions, choosing management techniques to test these questions, and applying
242 these techniques to the landscape using the principles of experimental design. Care is taken to
243 choose response variables that best tell whether the system is moving towards management
244 objectives, the resulting data is analyzed, and the findings from that data inform the next
245 management step. It is valuable to start with a simple adaptive management experiment testing
246 only a few alternatives, and then add complexity over time and to include researchers in the
247 management process so they can lend their expertise in the ecology of the system, the
248 development of the experimental design, and the analysis of the resulting data. The process of
249 adaptive management takes time, but the end product is a stronger knowledge of the system,
250 confidence that the management strategy developed in the process is the best alternative for the
251 site, and a management program that is scientifically valid and easy to defend. Increased use of
252 adaptive management will enhance our ability to improve decision-making over time.

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CASE STUDY USING EBIPM TO GUIDE RESTORATION

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In this study example, our overall goal was to restore desired native plant communities to pre-European settlement conditions with respect to ecosystem organization, structure, and function (Sheley et al. 2009). Once this was accomplished, we anticipated that invasive weeds would become a subordinate portion of the system (Pokorny et al. 2005). First, we assessed three sites using the Rangeland Health Assessment protocols in a heterogeneous ephemeral wetland dominated by invasive plants (spotted knapweed; sulphur cinquefoil; cheatgrass). Site 1 was had substantial meadow vole (*Microtis pennsylvanicus*) disturbance, which created increased bare-ground over areas without the rodent. In addition, this site had xeric soils with a low remnant stand of native functional groups relative to other sites within the area. Low remnant desired species suggested that species availability was low on this site. In contrast, the site 2 had low meadow vole disturbance and a relatively large remnant stand of native functional groups, but aridity of the site appeared to create mortality and decrease reproductive capacity of desired species suggesting that site availability and species performance does not favor desired native plants. Conversely, the third site was located adjacent to a wetland with high soil moisture (mesic) favorable to desired species with low meadow vole disturbance (site availability), but low remnant native vegetation (species availability).

Next, we used this assessment information to design an EBIPM strategy for each site by identifying ecological principles associated with each successional “cause” appearing 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

276 for seedling establishment. Ecologically, the processes in disrepair were likely associated with
277 dispersal of desired species and ecophysiological barriers to germination and emergence,
278 especially lack of water. Therefore, management on this site included seeding with desirable
279 species using a rangeland drill with depth bands and temporary irrigation (as a test).

280 At site 2, lack of disturbance appeared to limit safe sites for desired species because the
281 remnant stand of desired species was over 20% intact and likely produced desired species
282 propagules to re-occupy the site once the invasive weeds were controlled using herbicides
283 (altering relative species performance). In this case, we promoted natural seedling establishment
284 by lightly disking and imprinting the soil surface to collect moisture.

285 At the wettest portion of the area (site 3), species performance that involves the processes
286 imhabition and plant growth appeared adequate for desired species and the wet areas were too
287 wet for the invasive species to dominate. However, disturbance processes were inadequate to
288 create safe sites and desired species propagules were apparently absent. In this case, we disked
289 the site and seeded it with a diverse group of native species with traits useful to exploiting high
290 moisture conditions.

291 In this example, a three site EBIPM program was designed to repair the various processes and
292 address the cause of successional dynamics as ecological conditions vary across the landscape.
293 In spite of developing the most likely EBIPM program for the area, many assumptions and much
294 uncertainty about the outcome of management exists. The application of various strategies
295 should be implemented using an adaptive management statistical design (Reever-Morghan et al.
296 2006). It is imperative that untreated experimental controls are randomly located throughout the
297 site to allow a scientific test of the EBIPM program based on periodic assessments. Ideally,
298 alternative management could also be tested during management. In our assessment, this EBIPM

299 program increased the chance of restoration success by 66 percent over traditionally applied
300 integrated weed management (Sheley et al. 2009).

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SUMMARY

303 Enduring invasive plant management and ecosystem restoration can only be achieved if the
304 underlying ecological cause of invasion is altered to favor successional dynamics in toward a
305 desired plant community, and ultimately, their associated interactions with other essential
306 components of the ecosystem. Continued improvement in our ability to implement EBIPM
307 requires developing decision-making tools that link assessment, ecological processes,
308 management, and learning during management. We have improved our ecologically based
309 successional dynamics model to be more holistic by integrating assessment and adaptive
310 management with process-based principles that provide the direction to successfully apply tools
311 and techniques across landscapes. We believe that this framework provides the basis for EBIPM
312 and will enhance our ability to design and implement sustainable invasive plant management and
313 restoration programs.

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572	List of Figures.
573	Figure 1. Revised EBIPM successional model/framework describing rangeland assessment,
574	causes of succession, processes influencing these causes, and planning and management
575	guidelines, and adaptive management.