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By Jane Mangold

When managing rangeland impacted by weeds, land managers often encounter plant communities where remnant desired vegetation is very scarce. When rangeland is this degraded, simply controlling weeds with the expectation that desired plants will be released from competition and return to dominate the site over time might not be adequate. Introducing propagules (i.e., seeds) of desired species through revegetation might be required.

Ecologically Based Invasive Plant Management (EBIPM) serves as a decision-making framework for planning and implementing restoration and revegetation programs. This framework identifies three primary causes of succession or plant community change: site availability, species availability, and species performance. Site availability addresses whether there are spaces (niches) for a plant to grow on the site; species availability addresses whether there is a seed source available to occupy the site if space is available; and species performance addresses whether there are optimal levels of resources available that allow a plant to grow and reproduce ("perform") to its maximum capacity. Ecological processes influence each of these causes and are manipulated through management tools and strategies to direct plant communities from an undesired state to a desired state. Site availability is affected by disturbance; species availability is affected by dispersal and reproduction; species performance is affected by plant resource acquisition, response to the environment, life history strategy, stress, and interference with other plants. The EBIPM framework uses the three causes of succession and their associated ecological processes to guide managers through assessing site conditions, choosing weed control tools and restoration strategies, and planning follow-up management.

Site Availability, Species Availability, and Species Performance: A Three-Faceted Approach to Restoration

When weed performance is controlled through herbicides, grazing, biological control, mowing, or other methods, niches are opened in the plant community, creating site availability. Desired species, released from the competitive effects of the weed, often respond to the increase in open space or site availability, and reoccupy the site. However, on rangeland that has been dominated by weeds for a long time, availability of desired species can be minimal or completely lacking from the existing vegetation and seed bank. If weeds are controlled, but propagules of desired species are not available to occupy open niches, weeds are likely to return and natural recovery can be very slow or impossible. Unfortunately, many weed management activities focus on addressing site availability and species performance, while overlooking species availability. When this happens, the outcome of weed management can be ephemeral and disappointing over time. Introducing propagules of desired species and then promoting their persistence with management helps to direct the restoration process toward meeting long-term land-use goals. Along with actions to address site availability and species performance, species availability must be included in the weed management plan. Species availability is actively addressed through revegetation with desired species.

Land managers can be overwhelmed by the thought of addressing species availability through revegetation because it is a resource-intensive endeavor whose outcome is often dictated by random elements that are beyond our control, such as weather, seed predation, and soil heterogeneity. Guidelines for revegetating weed-infested rangeland are available through the EBIPM program[1] (Fig. 1). Although these guidelines are not a guarantee for success, they do provide an in-depth, step-by-step process for establishing desired vegetation. A rangeland health assessment might suggest that site availability needs to be repaired through active revegetation. If so, 14 steps are included in the revegetation guidelines, beginning with making a goal statement and ending with how to maintain the established, desired vegetation into the future. Following these steps can improve the odds of successful revegetation because they provide practical and effective concepts and methods to establish a desired plant community or return sites to conditions as similar as practicable to the predegraded state. Depending on the situation, restoration can entail many of the 14 steps or only a handful. As the revegetation plan is developed, land managers should carefully consider how each of the 14 steps addresses site availability (open niches), species availability (seeds and vegetative propagules), and/or species performance (growth and reproduction of species relative to each other). For example, site availability can be influenced by seedbed preparation and seeding method; species availability can be influenced by seed mix and seeding rate; and

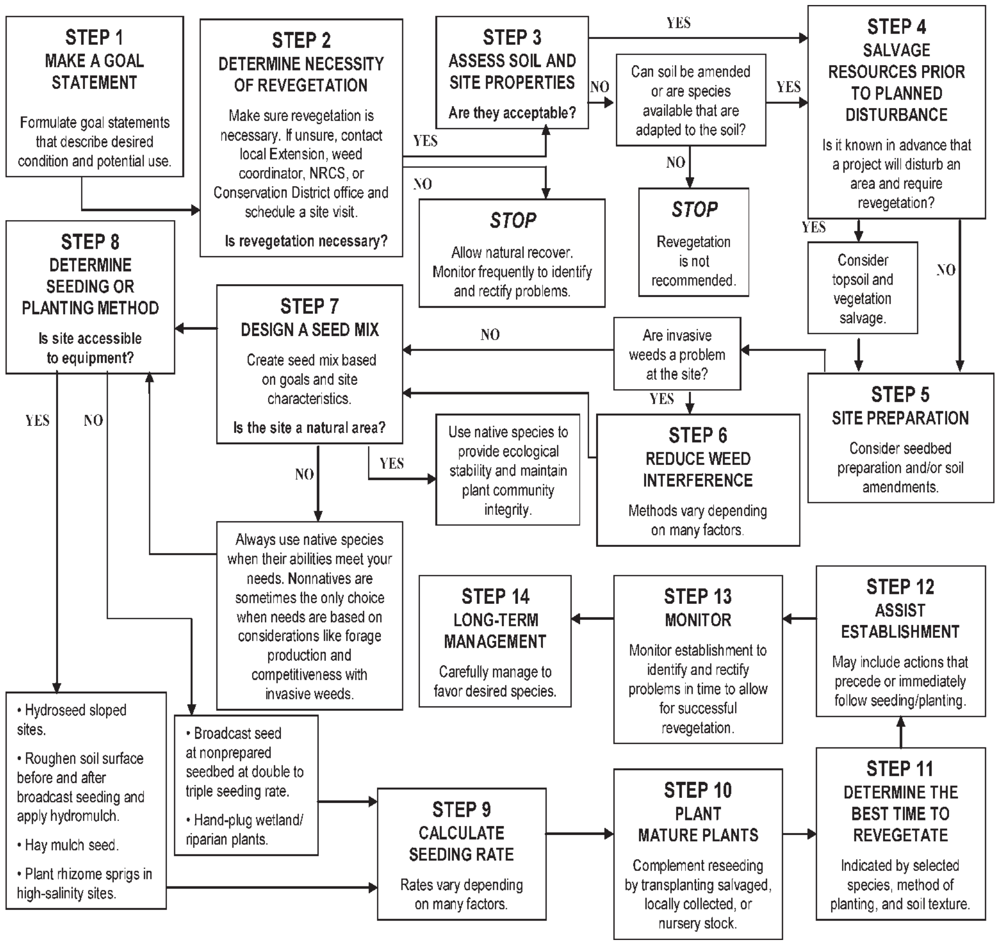

Figure 1. Fourteen-step flowchart to guide revegetation of weed-infested rangeland. Adapted from Sheley et al. (2008).[1]

species performance can be influenced by timing of seeding and long-term management.

Considering New Approaches to Restoration Using EBIPM

Rangeland restoration has historically relied upon relatively traditional agronomic practices that might not be as effective on landscapes that vary across time and space as they are in cropping systems where environmental conditions and species composition across a field are relatively uniform. Soil characteristics, elevation, aspect, precipitation, and plant community composition can vary widely across a rangeland management unit. A basic component of EBIPM is a rangeland health assessment to identify ecological conditions and processes at the site. Following the assessment, tools and strategies are developed that address those conditions and processes most in need of repair. By considering the wide variation in rangeland biotic and abiotic conditions in light of the three causes of succession, EBIPM offers ideas for new approaches to restoration. These ideas are not meant to be an exhaustive list, but rather to prompt further thought, discussion, and research into their application.

Site Availability

Following the site assessment, controlled disturbance to create site availability should complement the occurrence of natural disturbances on the landscape, such as burrowing by rodents. For example, instead of applying a tilling treatment across the entire site to be restored, carefully choosing areas to be tilled based on the absence of bare ground might create safe sites for desired species while minimizing unnecessary disturbance that could lead to further weed spread.

Soil characteristics should be considered as well when designing disturbance to create site availability. Weeds can alter physical (e.g., water infiltration rates), chemical (e.g., nutrient cycling, accumulation of allelopathic compounds), and biological (e.g., mycorrhizal fungi associations) soil characteristics. If such soil legacies are present, site preparation must include actions to remediate them and create safe sites that will be conducive to the establishment of desired species instead of weeds. An example could be the incorporation of activated carbon into the soil to alleviate the effects of allelochemicals.[2] Carbon additions have been proposed as a method of lowering soil nitrogen concentrations to create conditions more conducive to late seral native species instead of fast-growing weeds.[3]

Seeding technology aims to address site availability by placing seeds in a safe site, and extensive energy and resources have been devoted to developing the best equipment. However, research has shown that even modest improvements in seeding technology might yield substantial increases in seeding success.[4] At the same time, standard rangeland equipment can be difficult or impossible to use on rangeland that is too steep or rocky. Researchers and land managers should be encouraged to develop novel techniques for creating site availability in situations where revegetation equipment cannot be used. The use of domestic livestock as a method of designed disturbance is worthy of further investigation. Soil surface depressions created by hoof prints can accumulate and retain moisture for seeds and could serve as a microsite for colonization.[5]

Species Availability

Selecting species for revegetation should focus on choosing species that are productive as well as morphologically and functionally diverse. Productive, species-rich plant communities are less susceptible to reinvasion because a variety of desired species occupy a larger proportion of available niches and maximize resource uptake. In addition, diverse seed mixes can improve seedling establishment by increasing the probability that environmental conditions in the year of seeding will match the requirements of at least one or more species. Species differ in their traits and ranges of tolerance, so seeding a variety of species increases the odds that the mix will contain at least some species that will germinate and emerge under varying and unpredictable environmental conditions.[6]

Just as designed disturbance requires flexibility across rangeland so that natural conditions can be augmented and complemented, there should also be flexibility in choosing species appropriate for various locations on the landscape. All too often a species mix is created based on land management goals, and the same mix is then seeded across an entire project area. Seeding mixes could instead vary according to soil characteristics, topography, degree of weed infestation, and other factors commonly revealed through a rangeland health assessment. By placing appropriate species where they are most likely to establish and persist, the chances of long-term success through revegetation will be improved. This will also result in a mosaic of desired plants that are more similar to natural conditions.

Tools and strategies addressing species availability might also include identifying areas where successful establishment of desired species is critical (e.g., areas with high erosion potential, wildlife corridors) and then seed islands of species that are specifically chosen for their dispersal capabilities.[7] Such species might have a short juvenile period, produce copious amounts of seed, and produce seeds with long-distance dispersal capabilities. Because areas seeded to islands would be small relative to the entire area being managed, they could be intensely managed for successful establishment of seeded species. Islands could even be established using transplants or plugs so that the vulnerable seedling stage is avoided.

High seeding rates have been shown to increase establishment of desired species. In fact, recommended seeding rates for weed-infested rangeland are typically two to three times higher than standard seeding rates. Ultimately, seeding rate should be determined by examining the relationship between site availability and species availability. For example, if an overabundance of safe sites is present either naturally or through designed disturbance, then seeding rates should be high. High seeding rates can overwhelm the pool of available propagules, most likely weed propagules, and occupy the majority of safe sites. On the other hand, inundating a site with propagules of desired species when there are not adequate safe sites to accommodate them will result in disappointment and unnecessary expense.

Addressing species availability through multiple seeding phases is another avenue for improving revegetation success. Fast-growing, short-lived species could be seeded initially to provide immediate and direct competition with weeds that might be regenerating from the seed bank. These species could be mixed with midseral species that are intermediate in their growth rate and longevity. This first revegetation phase would aim to return conditions (e.g., abiotic and biotic soil characteristics) at the site to a state more conducive for growth of late-seral desired species. Finally, late-seral species that meet long-term management objectives would be seeded. This concept could be applied especially in weedy forb-infested rangeland. Here seeding phases can be used to first establish grasses while hindering the performance of the invasive forb with repeated broadleaf herbicide applications, then interseed desired forbs and shrubs during a second seeding phase.[8]

Species Performance

Controlling the performance of weeds in relation to desired species is a long-term endeavor. Time should be factored into revegetation plans. The length of time that weedy species have been present at a site and the biology of the target weed (i.e., ability to produce many long-lived seeds) will influence species availability and reinvasion potential. In turn, effectiveness and longevity of control measures can be compromised because seeded desired species have to compete with weeds during their establishment phase. Seed bank sampling can provide some insight into whether weeds will remain dominant at the site for some time. If seed bank sampling suggests a large weedy propagule pool, then multiple years of weed control prior to revegetation are recommended to reduce weedy propagule pressure.

Monitoring the performance of seeded desired species relative to potentially reinvading weeds will allow timely intervention and follow-up management to control species performance. If grasses have been seeded first in a multiphase seeding process as described earlier, applying control methods to hinder the performance of reinvading weedy forbs will be necessary. If seedlings of desired species appear to be struggling, intervention to improve their performance might

Figure 2. Bluebunch wheatgrass (*Pseudoroegneria spicata*) growing on long-term revegetation study site near Hamilton, Montana. Revegetation occurred 15 years prior to when picture was taken. Note prevalence of bunchgrass and absence of spotted knapweed (*Centaurea stoebe*) compared to nonseeded plot on left side of photograph.

be necessary. Intervention might include supplemental irrigation, precision fertilizer applications, or over-seeding to increase desired species propagules if or when future conditions are more amenable.

Monitoring the outcome of revegetation must be a long-term process and must be measured in the context of plant community successional trajectories. This requires dedicated individuals who are interested not only in implementing revegetation, but also evaluating effectiveness across short-, mid-, and long-term timeframes. Few studies have looked at long-term outcomes of revegetation of weed-infested rangeland, but one recent study suggested that initial trends are not indicative of long-term outcomes.[9] Four revegetation projects that integrated various forms of weed control and seeding on invasive forb-infested rangeland in Montana were resampled up to 15 years after revegetation. Some seeded populations remained very small for six or more years but then became highly productive and greatly suppressed the invasive forb spotted knapweed (*Centaurea stoebe*; Fig. 2). Other populations maintained high densities for three or more years but then became exceedingly rare or extinct. Additional long-term studies will help to assess the likelihood of favorable revegetation outcomes, identify good seeded species traits, and refine ecologically-based strategies for controlling site availability, species availability, and species performance during revegetation.

Using EBIPM to Guide Restoration: Examples From the Field

EBIPM can be used to guide restoration plans, ultimately improving the likelihood of success. One example comes from rangeland with seasonal wetlands in northwestern Montana where spotted knapweed and sulfur cinquefoil (*Potentilla recta*) were present.[10] Three sites were located that varied in the degree to which site availability, species availability, and species performance were either adequate or appeared to be in disrepair. Site availability appeared adequate at the "disturbed site" where small rodent activity provided safe sites for desired vegetation to establish, but few remnant native species remained and soils lacked moisture. Species availability appeared adequate at the "native site" where remnant native species were present, but rodent activity was absent and soils lacked moisture. Species performance appeared adequate at the "wetland site" where soil moisture was adequate, but rodent activity was absent and few remnant native species remained. After assessing the three causes of succession and their associated ecological processes occurring at each site, restoration tools and strategies were designed to augment those causes and processes that were in need of repair. Tools and strategies consisted of seeding and irrigating at the "disturbed site" (to improve species availability and species performance), tilling and irrigating at the "native site" (to improve site availability and species performance), and tilling and seeding at the "wetland site" (to improve site availability and species availability). After two years, short-term revegetation success was measured by an increase in cover and density of native grasses and forbs. At two of the three sites, use of EBIPM to guide the application of restoration tools and strategies increased cover and density of native grasses and forbs compared to nontreated controls.

A second example of applying EBIPM to restoration again comes from northwestern Montana on rangeland that was infested with spotted knapweed, sulfur cinquefoil, and a variety of other exotic perennial grasses and forbs.[11] In this example researchers increasingly addressed site availability, species availability, and species performance with a range of tools and strategies with the notion that integrated approaches would increase establishment of desired species compared to any singularly applied tool or strategy. Site availability was addressed by testing three herbicide treatments and two seeding methods, one of which was believed to increase seed placement into a safe site (drill-seeding); species availability was addressed by testing three seeding rates; and species performance was addressed by testing two cover crop treatments and herbicide applications. In most cases, integrated methods that addressed multiple causes of succession favored the establishment of desired vegetation compared to any one tool applied alone.

A final example of how EBIPM can guide revegetation comes from a study that investigated the importance of dispersal in influencing species availability and ultimately species performance. One of the principles associated with species availability and dispersal is that early arrival of less competitive desired species can increase establishment.[12] This principle can be applied in the field by timing the seeding of desired species to compete with invasive species. In a greenhouse study, timing of seeding of bluebunch wheatgrass (*Pseudoroegneria spicata*) was varied in relation to timing of seeding of cheatgrass (*Bromus tectorum*).[13] In one case, bluebunch wheatgrass had reached a four-leaf stage (approximately four weeks growth) when cheatgrass seed was introduced to the pots. In another case, bluebunch wheatgrass had reached a two-leaf stage (approximately two weeks growth) when cheatgrass was introduced to the pots. In the final case, bluebunch wheatgrass and cheatgrass were seeded into the pots at the same time. Plants were allowed to grow for about six weeks before above- and belowground biomass was harvested. Bluebunch wheatgrass that emerged earlier was less suppressed by cheatgrass; suppression was reduced by about 50% as bluebunch wheatgrass grew from being seeded at the same time as cheatgrass to being at a two-leaf stage when cheatgrass was introduced; suppression was reduced by another 50% when bluebunch wheatgrass was at the four-leaf stage when cheatgrass was introduced. At the same time, bluebunch wheatgrass was more likely to suppress cheatgrass growth as bluebunch wheatgrass grew from a seed to two- to four-leaf stage at the time of cheatgrass introduction. Even though this study was not conducted in the field, it demonstrates how influential dispersal order can be on species availability and performance and ultimately the outcome of revegetation efforts.

Summary

The ideas proposed and studies described in the previous sections serve as examples of how EBIPM can guide restoration of weed-infested rangeland. Many of the tools that will be used in EBIPM-guided restoration will still be the same (e.g., harrows, herbicides, drill seeders, seed mixes, cover crops), but they will now be applied with new insight and direction. Because restoration is a challenging prospect that often results in disappointing outcomes, thoughtful application of tools and strategies that are guided by our best understanding of site conditions, causes of succession, and ecological principles can improve success. Successful restoration guided by EBIPM will allow range managers to meet a variety of goals and protect the multitude of ecosystem services provided by rangeland.

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