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Linking Ecological Principles to Tools and Strategies in an EBIPM Program

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In ecosystems that are heavily invaded, it is common for the level of degradation to become so intense that the native plant seedbank is reduced. In these cases, active restoration that includes revegetation efforts and stress manipulations through herbicide use, tillage, periodic flooding, prescribed burning, or timely strategic grazing are often necessary to recover certain ecosystem functions. In wildlands and rangelands, herbicides and grazing are generally the most widely used techniques for the control of invasive and weedy plants.

Unlike cropland environments where all plants, except the crop, are considered to be weeds, in wildlands and rangelands there is often only one or a few invasive plants that are the target of control measures. These plants are generally growing in association with several desirable species. Selectivity is then critical when developing an effective weed management program. Both strategic grazing and herbicides can be applied selectively to alter the trajectory of a plant community to a more desired and functional state.

Ecological Principles Guiding Management of Invasives in Rangelands

The use of a particular management tool for control of invasive and weedy plants often depends on the life cycle of the target plant or plants, as well as the life cycle of the desirable plants within the community. For example, different treatment timings or options will be necessary when targeting early season annual grasses, such as downy brome (cheatgrass) (*Bromus tectorum* L.), red brome (*Bromus rubens* L.), or ripgut brome (*Bromus diandrus* Roth.) compared to late season annuals, including medusahead (*Taeniatherum caput-medusae* [L.] Nevski) or barb goatgrass (*Aegilops triuncialis* L.). Similarly, treatment timing of early season invasive annual broadleaf species, such as Italian thistle (*Carduus pycnocephalus* L.) and blessed milkthistle (*Silybum marianum* [L.] Gaertn.), can be very different from that of the late season annual broadleaf species, including yellow starthistle (*Centaurea solstitialis* L.).

Various aspects in the control of perennial grasses and broadleaf species, as well as woody species, will also be very different from those of annual species, in particular with regard to timing. Regardless of whether mechanical, cultural, or chemical control methods are employed, the timing of their use should be aligned with the most vulnerable stage of development of the target species and, hopefully, the least vulnerable life cycle stage of the desirable species. While this cannot always be achieved, there are many situations where desired selectivity is possible with the use of a variety of management tools, including grazing and nonselective or broad spectrum herbicides.

To attain selective management of one or a few problematic species, it is important to understand the biology of the species present on a site and the ecology of the plant and animal community. It is also important to consider the land use objectives for any area targeted for invasive plant management. For example, the choice of control option, particularly with herbicides, can differ depending on whether the land use objective is forage production for livestock, timber production, preservation of native or endangered plant or animal species, wildlife habitat development, water management, or recreational land use and maintenance. To effectively achieve the desired outcome, the choice of an appropriate invasive plant management strategy may be complicated and is best achieved through a successional invasive plant management approach provided by an Ecologically Based Invasive Plant Management (EBIPM) program.[1,2]

Key Ecological Principles Linked to Grazing Annual Grasses

Grazing is considered a natural process in grasslands. As a result of the process of grazing, livestock remove litter, recycle nutrients, stimulate tillering of perennial grasses, and reduce seedbanks of competitive annual plants. Livestock grazing can be one of the most useful tools to keep rangelands in good condition and maintain optimum production. Rangelands are often diverse with native species having multiple life strategies. There are numerous scientific studies documenting that proper grazing with livestock can facilitate resistance to invasion as well as recovery of rangeland services (see reviews by Krueger-Mangold et al. and DiTomaso).[1,3] The potential of grazing is promising because no other vegetation management tool has the prospect to generate revenue while improving rangeland. Grazing has been shown to alter species composition from less desirable species to desired species, increase the productivity of selected plant species, increase the nutritive quality of the forage, and increase the diversity of habitat. Ultimately, using livestock to manage

invasive annual grasses will have positive effects on the landscape and help managers achieve their economic goals.

Two principles are key in guiding the management of annual grasses using grazing. First, because annual grasses must produce seeds to survive, it is critical to prevent them from reaching the flowering and reproductive stage. Most annual grass seeds live for only a few years in the soil. By reducing the number of seeds produced, seed banks will eventually be depleted, and propagule pressure will be reduced dramatically. Even partial reduction in seed production from grazing can be helpful. Second, by maintaining vigorous and healthy desirable perennial vegetation, successful establishment of annual grasses will be greatly reduced. The ecological fundamental is to create opportunities to shift the competitive advantage to the perennial desired species. For example, continuous grazing on perennial plants weakens the root system as the plant sacrifices roots to regenerate shoot growth for photosynthesis. Fewer roots of desirable grasses allow excess water and nutrients to be utilized by annual grasses.

Targeted strategic livestock grazing is based on fundamental ecological processes, including an understanding of the plant resource acquisition, response to stress and other environmental conditions, and competitive interactions. All these processes are linked to species performance. If desired plants can be protected from herbivory at critical periods in their life cycle, a more robust and healthier population will better resist establishment and dominance of invasive plants.

Key Ecological Principles Linked to Herbicide Use

Most herbicides are selective only within certain rates, environmental conditions, and methods of application. In many cases, even selective herbicides can kill tolerant desirable vegetation under particular conditions. The factors involved in plant susceptibility to herbicides are influenced by germination timing, growth stage and rate, morphology of roots, growing points, and leaf characteristics, as well as genetics of each species.[4] By placing the herbicide only in contact with the invasive plant, it is possible to achieve selectivity with an otherwise nonselective compound. This can be accomplished with both preemergence and postemergence herbicides. By choosing the most appropriate and effective herbicide, applying it at the correct rate and at the most appropriate timing, and using an application technique that will maximize its effectiveness and selectivity, it is possible to achieve successful invasive plant control while minimizing damage to nontarget species.

Selective Use of Grazing for Annual Grass Management

Grazing can be used as part of an integrated management plan within the EBIPM framework. For annual grasses, a process termed "Green and Brown" is a simple method for managing livestock while allowing perennial grasses to reoccupy the invaded sites and generate more animal production. A "Green and Brown" strategy utilizes grazing when invasive annual grasses are green and vulnerable, but desired species are brown, dormant, and less vulnerable. This strategy, also known as time-controlled, short-duration, high-intensity grazing, can create a desired landscape that increases the competitive balance in favor of desired species.

The underlying basis of the "Green and Brown" grazing strategy depends upon an understanding of proper stocking rates, forage palatability, and class of livestock. Using this strategy, stocking rates must be high enough to severely damage the annual grasses, but animals must be removed prior to growth of desired perennial plants in mid-spring. Grazing annual grasses should be a part of a long-term approach to managing invasive annual grasses, as annual grasses often rapidly return when animals are removed.

Within the context of an EBIPM program, managed grazing using a "Green and Brown" strategy is primarily designed to alter relative species performance by reducing seed production in undesirable annual grasses compared to more desirable perennial grasses. This can influence species availability, as well as site availability in creating specific strategic disturbances. It is accomplished because annual grasses have a growth period different from most native, or non-native, perennial grasses. They germinate from the late fall to early spring when precipitation and temperatures are sufficiently high. At this time, most perennial grasses have yet to break vegetative dormancy.

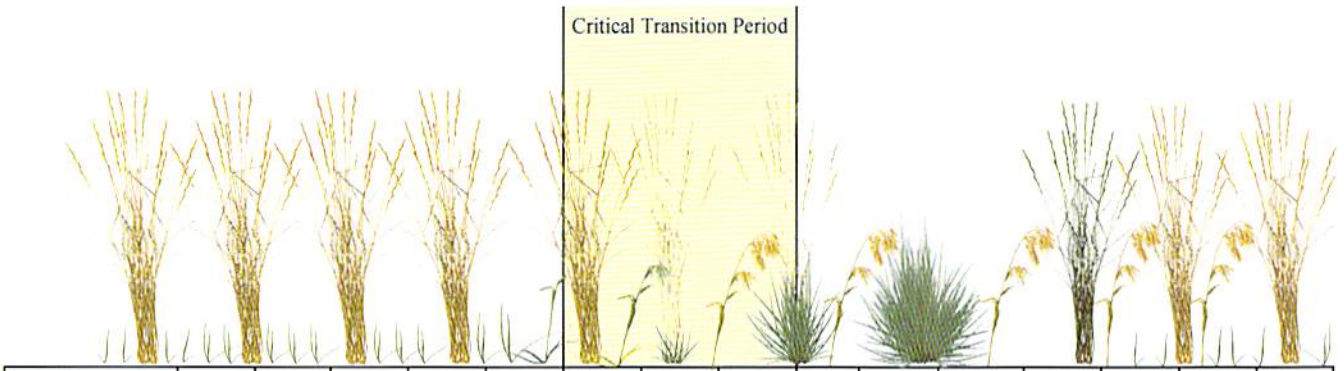
The difference in germination timing in annual grasses and growth of perennial grasses makes invasive annual grasses palatable, highly nutritious, and preferred forage by livestock. During this grazing period perennial grasses have low nutritive value and are also tolerant to grazing (Fig. 1). When grazed at the right time, livestock can dramatically reduce seed production in annual grasses by foraging on the top portion of the plant. This can be a very effective strategy for long-term control of annual grasses, which depend upon seed production to sustain their populations.

If the soil remains moist into early summer, light grazing can often stimulate more seed production in annual grasses compared to no grazing. To successfully manage invasive annual grasses, grazing should be high intensity and short duration. This will have a negative impact on annual weeds and, with proper planning, can allow for recovery of desired perennial species.

Grazing to Prevent Annual Grass Invasions

Even when no invasive annual grasses are present, the principles of a "Green and Brown" strategy can be used to keep desired perennials growing vigorously. To accomplish this, grazing timing for desired perennial species should occur when they are dormant (brown), but still have adequate nutritive value. This will allow full recovery without reducing their vigor the following season.

In landscapes where the objective is preventing infestation of annual grasses, animals can remove perennial grass standing litter that blocks light and impedes vegetation growth. In addition, reducing the fine fuels loads through grazing can also decrease the risk of catastrophic wildfires.



Grazing Period	Yes	Yes	Yes	Yes	Yes	maybe	No	No	No	Maybe	Maybe	Maybe	Yes	Yes	yes
Perennial Grasses	Senescence		Dormancy				Growth initiation	Leaf growth	Boot stage & seed head emergence		Flowering & seed development		Seed hardening & scatter & senescence		
Annual Grasses	Germination		Growth initiation			Leaf growth	Boot Stage	Flowering & seed Development		Seed hardening & scatter		Death	Germination & growth initiation		
Month	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec

Figure 1. Visual representation of the "Green and Brown" grazing strategy. Grazing periods are imposed based on the actual plant growth stage for both desired perennial grasses and annual grasses. The calendar months are used only as a general reference; always graze by plant growth stage paying close attention to early green-up of perennials. This also illustrates the critical transition period for removing livestock.

Grazing in an Annual Grass Restoration Effort. In monotypic stands of invasive plants, where active restoration efforts are necessary, a "Green and Brown" grazing strategy can be used to reduce the amount of annual grasses by repeated grazing in both fall and early spring. Since desirable dormant perennial grasses are not present in the system, multiple years of intense grazing of invasive grasses can be used to deplete the seed bank. Subsequent reseeding of desirable plants will minimize annual grass competition. Once desirable perennial grasses are established, grazing management practices can continue through a "Green and Brown" strategy.

Selective Use of Herbicides for Invasive Plant Management

Choosing the Proper Herbicide for Selective Control

The most widely used grassland herbicides in rangelands are those that have postemergence activity.[3,4] These include 2,4-D, aminopyralid, aminocyclopyrachlor, clopyralid, dicamba, picloram, triclopyr, chlorsulfuron, metsulfuron, rimsulfuron, imazapic, and glyphosate (Table 1). With some of these herbicides, particularly aminopyralid and clopyralid, most broadleaf species are fairly tolerant because they target primarily species within the Asteraceae, Fabaceae, and a few other plant families. Other herbicides, including chlorsulfuron, rimsulfuron, metsulfuron, sulfometuron, imazapic, and imazapyr, are all amino acid inhibitors and can range in their selectivity from primarily broadleaf control (metsulfuron), to broad spectrum control (chlorsulfuron, rimsulfuron, and imazapic), to nonselective compounds (imazapyr and sulfometuron). Among the herbicides listed in Table 1, many are applied only postemergence, some are applied only preemergence, and yet several others can be active when applied either pre- or postemergence.

Even herbicides that are considered broad spectrum can vary in their selectivity within a single plant family. For example, imazapic is very effective on medusahead, downy brome, ripgut brome, barb goatgrass, red brome, soft brome (*Bromus hordeaceus* L.), and other annual grasses.[5] Yet, the same herbicide is fairly safe on several native perennial grasses and on native Asteraceae or Fabaceae species. Because of this selectivity, imazapic is of particular interest as a tool for controlling annual grasses during grassland restoration and establishment of perennial forage grasses.

In another example, two closely related herbicides, aminopyralid and clopyralid, demonstrated widely different responses for the control of coast fiddleneck (*Amsinckia menziesii* [Lehm.] Nelson & J. F. Macbr. var. *intermedia* [Fisch. & C.A. Mey.] Ganders). Coast fiddleneck is a native plant to grasslands and rangelands, primarily in the western United States. However, it contains pyrrolizidine alkaloids which can produce chronic poisoning in cattle, horses, and swine. Although it is considered a desirable native in wildland regions, it is undesirable when it occurs at high density within rangelands. Clopyralid does not provide effective control of coast fiddleneck and often results in an increase in its density following yellow starthistle control.[6] In contrast, aminopyralid gives almost complete control of coast fiddleneck when applied in the winter growing season.[7] The choice of an herbicide can greatly influence the plant community response following treatment. For this reason, it is important to understand the ecology of the system and how a particular product will influence both target and nontarget plant species.

Influence of Timing on Herbicide Selectivity

Timing of herbicide applications can not only determine the effectiveness of the treatment, but also impact desirable vegetation. For the most part, younger plants are easier to kill

Table 1. Selectivity of terrestrial herbicides used in natural areas and rangelands

Selectivity	Herbicides	Timing
Broadleaves	2,4-D, dicamba, triclopyr	Postemergence
	Aminopyralid, aminocyclopyrachlor, clopyralid, picloram, metsulfuron	Pre- and Postemergence
Grasses	Clethodim, fluazifop-P-butyl, sethoxydim	Postemergence
Annuals	Paraquat	Postemergence
Broad spectrum	Chlorsulfuron, rimsulfuron, imazapic	Pre- and Postemergence
Non-selective	Glyphosate	Postemergence
	Hexazinone, tebuthiuron	Preemergence
	Imazapyr, sulfometuron	Pre- and Postemergence

than older ones, and rapidly growing plants are more susceptible to herbicides than slower-growing ones. This is true for annuals and perennials.[4] However, treatment timing can also be a means to achieve placement selectivity, where targeted plants are at a susceptible stage and nontarget plants are tolerant to the herbicide. In this situation, nonselective foliar herbicides can be used selectively to control emerged annual invasive plants before emergence of more desirable species or bud break in woody species. For example, when medusahead was treated with low rates of glyphosate from early seedling to the tillering stage, control was >95%. Moreover, this early timing allowed a portion of the broadleaf flora to escape injury by emerging after the application.[8]

In California rangelands, early season applications of clopyralid or aminopyralid when yellow starthistle was in the rosette stage resulted in a two- to sixfold increase in desirable annual grass forage production compared to later season applications at the bolting stage.[7] This was attributed to a release of grasses from competition when yellow starthistle was controlled early in the season.

Achieving Selectivity With Herbicide Rate

Herbicide selectivity within a particular plant community is often rate dependent. Although lower registered rates may not always provide sufficient control of target species, higher registered rates can result in loss of selective control and injure nontarget plants.[4] For example, at increasing imazapic rates, annual grass cover decreased and the plant community shifted toward tolerant perennial grasses or broadleaf species, particularly species in the Asteraceae.[5] This shift may be a desirable outcome in revegetation efforts designed to restore important native Asteraceae species or tolerant perennial grasses. Alternatively, if the goal is to selectively remove an invasive grass (e.g., medusahead, downy brome) in a rangeland system that also has other more desirable annual forage grasses, such as slender oat (*Avena barbata* Pott ex Link), soft brome, and Italian ryegrass (*Lolium perenne* L. ssp. *multiflorum* [Lam.] Husnot), then the use of imazapic is not likely to provide the desired results.

Aminopyralid is a synthetic auxin herbicide used for pre- and postemergence control of many noxious and invasive species, particularly thistles and knapweeds. Although it is safe on established grasses and generally safe on most germinating grasses, when applied preemergence at high labeled rates it can control medusahead[8] and also suppress seed production in Japanese brome (*Bromus japonicus* Thunb. ex Murr.).[9] In annual grasslands, where the dominant species includes invasive thistles and medusahead, high labeled rates of aminopyralid resulted in a shift to more desirable annual forage species such as slender oat and Italian ryegrass.[10]

Achieving Selectivity Control Through Application Technology

Herbicides can be applied preemergence to soil prior to invasive plant germination, or postemergence to the foliage or stem. The application can be as broadcast treatments over large areas, directed or spot applications to individual plants or small patches, or by specialized application techniques, including stem treatments and drizzle or wicking techniques.[4] Broadcast treatments are best in areas with large infestations and few, if any, sensitive nontarget species. Application are made to rangelands by a number of methods, including boom sprayers attached to fixed wing aircraft, helicopter, tractors, ATVs, or other specialized ground applicators. These techniques can cover large areas quickly and are more economical, but can also damage sensitive nontarget species.

When selectivity is required, but cannot be achieved with broadcast applications, directed or spot treatments are the most appropriate method of herbicide application. Directed or spot treatments have the advantage of selectively removing targeted invasive plants, and although they can be more labor intensive and expensive, they tend to use less total herbicide per area compared to broadcast applications.[4] In addition, spot treatments are typically used to control early weed invasions or to prevent the

spread of small infestations. Spot or directed treatments also allow selective control of a particular weed with otherwise nonselective or relatively nonselective postemergence herbicides. These techniques can help to shift a plant community to a more desired state, by selectively removing problematic species.

In wildlands or rangelands, spot treatments can be made by backpack sprayers equipped with handheld booms consisting of multiple nozzles. More typically, backpack sprayers are configured using a single nozzle directed at the target species. Another recently developed application technique is the drizzle method which ejects a fine spray stream 20 to 30 feet that breaks into large droplets when it contacts the plant. The drizzle technique applies herbicide at a higher concentration, but at a considerably lower volume than foliar applications. As another advantage, the spray stream reduces drift and allows the applicator to treat invasive plants on steep banks, or areas with limited access.It is also possible to achieve selective control of a particular invasive plant with otherwise nonselective or relatively nonselective postemergence herbicides by employing a wick applicator. These can be either hand held or vehicle-mounted boom wipers that can be applied as a spot treatment or even selectively as a broadcast application. Vehicle-mounted wicks can be adjusted in their height above the ground to obtain selective control of taller undesirable vegetation.[4,11]

While woody invasive species can be treated with postemergence applications, many can be more effectively managed using stem treatments. Stem treatments can be applied through several techniques, but primarily by cut stump, stem injection (hack-and-squirt), or basal bark methods. The use of these methods depends on the number and diameter of stems and the woodiness of the bark. These techniques are only used on resprouting species, as species that do not resprout can be easily controlled using only cutting. The best treatment timing for all three methods and herbicides is in mid-summer to early fall when photosynthates are translocating at their maximum rate to the below ground reproductive structures.

Integrating Tools and Strategies in an EBIPM Systems Approach

Specific tools and strategies for invasive plant management will be more successful when they are linked to the ecological principles that will ultimately affect the processes that favor desired plants and not undesired ones. Having a good understanding of these principles will allow for better integration of available tools. We have provided management tools and strategies, using herbicides and grazing, that utilize an EBIPM systems approach to managing invasive plants.

The principles of Integrated Pest Management and EBIPM emphasize the recovery of ecosystem function that can include energy flow, nutrient cycling, soil water retention, and other functions. This sustainable approach provides a context for managing invasive plants at an ecosystem-centered level, rather than focusing on the control of a specific invasive plant or the use of a pest control technology. For this reason, all available tools should be considered during development of integrated weed management programs, and those selected should optimize attainment of specific management objectives. The ultimate goal is to provide ranchers and land managers with economical and sustainable management programs that maximize forage production or restore and preserve desired ecosystem functions, including reducing the susceptibility of their lands to reinvasion or invasion by other noxious weeds.

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