WHITE PAPER

TECHNIQUES FOR RESTORING NATIVE PLANT COMMUNITIES IN UPLAND AND WETLAND PRAIRIES IN THE MIDWEST AND WEST COAST REGIONS OF NORTH AMERICA

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TECHNIQUES FOR RESTORING NATIVE PLANT COMMUNITIES IN UPLAND AND WETLAND PRAIRIES IN THE MIDWEST AND WEST COAST REGIONS OF NORTH AMERICA

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ABSTRACT

Prairies are unique from other biomes, in that they are open habitats comprised mainly of herbaceous plants with only a scattering of trees. One of the important ecological attributes of prairies is their high plant species richness. Midwest and West Coast prairies exhibit major differences in climate, vegetation types, disturbance regimes (e.g., fire and grazing), and soils, which provide an important context for restoration activities. Most prairies in the Midwest and West Coast regions have been reduced to less than 1-2 percent of their former size. The remaining remnant prairies are generally small in comparison to historic sizes, exist in isolation and are degraded due to invasion of introduced species and disruption of ecological processes such as fire. Successful ecological restoration of land that was originally prairie requires accomplishing certain objectives: 1) reducing the abundance of non-native species and woody vegetation, 2) reducing the weed seed bank, 3) improving the competitive environment for natives, 4) successful planting of native species, and 5) successful post-seeding management.

After reviewing the scientific literature on prairie restoration in the Midwest and the West Coast regions of the United States, I suggest various restoration techniques for addressing the five objectives, including: cultivation, herbicides, flaming/infrared burning, solarization, carbon addition/nutrient immobilization, mycorrhizal inoculation and implementing various seeding methods and seed mixes. Short and long-term management techniques include hand weeding, herbicides, mowing, grazing and prescribed burning. One of the essential lessons learned by restoration ecologists and practitioners trying to restore native prairie, is that there is not one technique or combination of techniques that work for all restoration sites, i.e., there is no magic bullet. Restoration techniques will need to be site specific and may depend on many things including past disturbance events, assemblage of plants, including non-natives and natives, and site conditions such as soils, topography, hydrology, and climate.

INTRODUCTION

In this paper, I begin by discussing why prairies are important, how they differ in the Midwest and West Coast regions and why prairies have all but disappeared. I then make a case for why restoration efforts are needed to save the remaining prairies and discuss various site preparation, seeding and planting, and post-seeding management techniques used to restore native prairies. I follow up with some concluding remarks on methods that may prove useful in the future at reducing weeds and the seed bank and make some final recommendations on research needs and techniques for restoring prairies.

I reviewed the scientific literature on prairie restoration techniques used in the Midwest and the West Coast regions of the United States to evaluate their effectiveness in meeting the following objectives: (Table 1)

1. Kill existing non-native vegetation
2. Control non-native seed banks
3. Improve the competitive environment for natives
4. Successful planting of native species
5. Successful short and long-term management

Prairies and grasslands are unique from other biomes, in that they are open habitats comprised mainly of herbaceous plants with only a scattering of trees. One of the important ecological attributes of prairies is their high plant species richness, with as many as 904 taxa of native plants, including 686 forbs, 108 grasses, and 110 sedges occurring in tallgrass prairies throughout the Midwest region of the United States and Canada (Ladd 1997). As much as 65 percent of the biomass of prairie plants is underground (Miller 1997, Mlot 1990). The rhizosphere beneath the prairie is comprised of a rich diversity of organisms crucial for the health of prairies, including rhizobial-root nodules that fix nitrogen and mycorrhizal fungi that extract and transport vital nutrients to plants (Miller 1997). Prairies also provide a home for a rich diversity of fauna, including birds, mammals, butterflies, and other invertebrates, some of which are almost entirely dependent on the open habitat and type of plants that reside in prairies (Mlot 1990).

Midwest and West Coast prairies are unique

Midwest and West Coast prairie systems exhibit major differences in climate, vegetation types, disturbance regimes (e.g., fire and grazing), and soils, which provide an important context for restoration activities. Continental weather patterns influence the Midwest while maritime weather patterns influence the West Coast. For example, in the Midwest most precipitation falls during storms in the spring and summer months, whereas along the West Coast most precipitation occurs in the fall, winter and spring months, with summer months remaining relatively dry (Keen 1987). As a consequence, warm season grasses are generally dominant in the Midwest, while cool season grasses are dominant along the West Coast (Packard and Mutel 1997, Schoenherr 1992). Historically, prairie fires in the Midwest were ignited by both lightning and Native Americans, and may have occurred in the fall, spring and summer months (Howe 1994, Anderson 1997), while most of the burning in the West Coast prairies was ignited by Native Americans in the fall (Whitlock and Knox 2002). Midwest prairies experienced high-intensity grazing pressure by bison before European settlement (Steuter 1997); in contrast, West Coast prairies experienced much lower levels of grazing pressure, mainly by elk and deer (Heady 1977, Holland and Keil 1995). Finally, the top soils in the Midwest prairies were historically deep, between 50-70 cm in depth (Kline 1997), while West Coast prairie systems have generally shallow top soils, typically between 0-36 cm in Washington (Crawford and Hall 1997) and up to 50 cm in California (Heady 1977). Some of the differences, including soil depth, vegetation types, and precipitation patterns may influence restoration methodology and the timing of techniques for the different regions.

The loss and degradation of prairies

Native tallgrass prairie originally covered more than 143 million acres in the Midwest region of North America, extending from Texas to Canada and from Nebraska to Ohio. This vast prairie system developed and was maintained by dry climatic conditions, fire, and grazing by vast herds of bison and other ungulates (Axelrod 1985, Anderson 1997, Kline 1997, Kurtz 2001). Only 1-2 percent of Midwest prairies remain; most having been converted to farmland and pasture (Mlot 1990, Howe 1994). Although the native prairies along the West Coast of North America are less extensive and not as well known as the Midwest prairies, they are nevertheless important ecosystems. Prior to European settlement, these native upland and wet prairies once occupied 22, 1, and 0.16 million acres along the West coasts of California, Oregon and Washington, respectively (Schoenherr 1992, Crawford and Hall 1997, Christy and Alverson 2004). It is believed that these prairies were maintained primarily by climatic conditions, combined with natural and aboriginal fires (Boyd 1986, Holland and Keil 1995, Christy and Alverson 2004). With the advent of fire suppression, invasion by non-native plants, over-grazing, encroachment of woody vegetation, alteration of hydrologic regimes, conversion of native prairie to agriculture, and pasture and urban development, less than 1 percent of these original prairies remain intact (Heady 1977, Schoenherr 1992, Crawford and Hall 1997, Christy and Alverson 2004).

Some scientists and conservationists consider prairies and grasslands to be one of the most imperiled habitats in North America (Bryer et al. 2000).

The remaining remnant prairies in both the Midwest and West Coast regions are generally small in comparison to historic sizes, exist in isolation and are degraded due to invasion of introduced species and disruption of ecological processes such as fire. Fragmentation can lead to decreased vigor and reproductive output of many of the plants and animals due to inbreeding depression and other genetic problems associated with small and isolated populations (Reinartz 1997, Knapp and Dyer 1998, Schultz and Chang 1998, Wilson et al. 2003). With the introduction of non-native species and fire suppression, many endemic plants and wildlife that once thrived in prairie systems are becoming less common or are threatened with extinction (Clark and Wilson 2000, Schultz et al. 2003, Schultz and Hammond 2003). For example, in Oregon, the endemic Willamette daisy (*Erigeron decumbens*), white topped aster (*Aster curtus*), and the Fender's blue butterfly (*Icaricia icarioides fenderi*) are federally listed as endangered. Schultz et al. (2003) estimates there to be fewer than 2000 of the Fender's blue butterfly remaining in the Willamette Valley in Oregon. The declining population of Fender's is due in large part to the disappearance of prairie habitat and the reduced numbers of their host plant, Kincaid's lupine (*Lupinus sulphureus* ssp. *kincaidii*), and native nectar plants. Grass species that were historically common along the West Coast, but are disappearing include: Idaho fescue (*Festuca idahoensis* var. *roemeri*), California oatgrass (*Danthonia californica*) and purple needlegrass (*Stipa pulchra*). These plants and animals as well as others will be lost forever unless native prairies are preserved and restored.

The need for restoration

The first documented prairie restoration occurred in Wisconsin at the University of Wisconsin Arboretum in the 1930s, and is known as the Curtis Prairie (Cottam and Wilson 1966, Sperry 1994). Since that time many more prairie restorations have followed, most of which have taken place in the Midwest. Prairie restoration is a process that attempts to recreate the natural processes and vegetation of historic prairies, often by using relatively intact remnant or relict prairies that have somehow escaped being plowed as models (Mlot 1990).

Ecological restoration of land that was originally prairie, or enhancing intact but degraded prairies requires: 1) reducing the abundance of non-native species and woody vegetation, 2) reducing the weed seedbank, and 3) increasing the abundance of native plants, including rare and endangered species and native forbs critical as nectar sources for butterflies and other animals. In addition there is a need to restore the ecosystem processes such as fire and grazing (Boerner 1982, Howe 1994, Pauly 1997, Maret and Wilson 2000, Copeland et al. 2002, Knapp and Seastedt 1986, Hatch et al. 1999), reduce nutrients such as nitrogen (Davis 2001, Blumenthal et al. 2003), and possibly enhance soil microbial communities, such as mycorrhizal fungi (Haselwandter 1997, Smith et al. 1998, Hartnett and Wilson 1999, Klironomos 2003). Restoring ecosystem processes may enhance conditions that promote natives and help to insure the long term success of prairie restorations (Davis 2001).

Reducing non-native species is imperative because they may change fire regimes by altering fuels (Parker and Reichard 1998) and alter soil structure and ecosystem processes such as nitrogen and carbon cycling (Jastrow 1987, Wedin and Tilman 1990, Christian and Wilson 1999). Soil structure, measured as percent soil aggregation, was significantly higher under Illinois native prairie than under pasture dominated by Eurasian grasses (Jastrow 1987, Mlot 1990). Jastrow (1987) suggests that length and time of growing season, root morphology and levels and diversity of mycorrhizal colonization might be possible mechanisms for increased soil structure. Soil nitrogen levels may be higher in fields dominated by introduced rhizomatous grasses because they tend to promote higher levels of nitrogen mineralization than native bunch grasses (Wedin and Tilman 1990, 1996, Davis 2001). These higher levels of nitrogen often favor the introduced and domesticated Eurasian species because they tend to be nitrophilic, whereas native prairie plants are not. Christian and Wilson (1999) found that fields dominated by the non-native grass *Agropyron cristatum* had lower plant diversity and root mass which may have led to less carbon in the soil than native undisturbed prairies.

Non-natives may also reduce biodiversity (Schultz et al. 2003) and outcompete natives (Parker and Reichard 1998, Bakker and Wilson 2001). An experimental study in California found that the rare annual forb *Amsinckia grandiflora* performed better and had higher reproductive output when planted into a stand of the native bunchgrass *Poa secunda*, compared to being planted into a stand of non-native annual grasses (Carlsen et al. 2000). Bakker and Wilson (2001) found that the competitive ability of the non-native grass *Agropyron cristatum* (crested wheatgrass) in Saskatchewan allowed it to persist, invade new territories and reduce establishment of natives. Non-native species have also led to the decline of the endangered Fender’s blue butterfly in Western Oregon because competition has reduced the population of the butterfly’s host plant, Kincaid’s lupine and native nectar plants (Schultz et al. 2003). The existence of non-natives at a site for an extended period of time can also lead to a large number of weed seeds being deposited into the seed bank (Milberg 1992, Sveinson and McLachlan 2003). This coupled with the loss of native seeds in the seed bank due to predation, microbial disease, senescence and other factors (Clark and Wilson 2003) can lead to conditions where soils beneath restoration sites are often seed limited.

Restoration techniques

Prairie restoration practitioners and researchers use a variety of techniques to restore and enhance prairies. These techniques can be roughly divided into: 1) site preparation, 2) improving the competitive environment for natives, 3) seeding and planting and 4) post-seeding techniques (Table 2). Site preparation consists of killing, suppressing or removing the existing non-native and woody vegetation and the seed bank. I discuss a variety of restoration techniques that address these concerns, including: cultivation, herbicides, flaming or infrared burning, solarization, and combining treatments. Techniques for improving the competitive ability of natives include reducing nitrogen through carbon addition and restoring mycorrhizae diversity and abundance. In the seeding and planting section, different seeding methods and seed mixes will be addressed. In the post-seeding section, I discuss short-term management techniques, including: hand weeding, herbicides, mowing, grazing, and adding additional seed. The long-term management techniques that can restore ecological processes and functions include burning, grazing and mowing.

The main focus of this paper will be to discuss techniques for restoring old fields that are dominated by non-native species and where there is a need to make a fresh start. Restoring existing prairies that have some proportion of natives and are relatively intact can be enhanced by techniques discussed in the seeding and planting and post-seeding sections of this paper.

RESULTS OF THE LITERATURE REVIEW

SITE PREPARATION TECHNIQUES

The first step, and probably the most important in restoring a native prairie, is proper site preparation. Site preparation sets the stage for the restoration by creating the seedbed for native planting. Without proper site preparation, seeding, planting, and post planting management will likely be unsuccessful.

Cultivation

Tilling, disking, plowing, and harrowing are often used to temporarily reduce or suppress non-native grasses and forbs and prepare a seedbed prior to sowing in native prairie seeds. However, the effects of these site preparation techniques on developing native plant communities depends on the frequency, intensity, and depth of tilling. Repeated light or shallow disking over one or two seasons often helps to deplete the weed seed bank (Mohler 1993, Morgan 1997, Barberi 2002). Tilling that produced 100 percent bare ground and a "neighbor-free" site led to higher establishment rates of native seedlings than plots that were lightly tilled (Wilson and Gerry 1995). Although there are advantages to tilling, the process can lead to increased germination of buried weed seeds because seed is brought to the soil surface.

A mathematical model developed by Mohler (1993) to explore the effect of tillage on emergence of weed seedlings suggests that in situations where a large number of weed seeds are mixed or buried in the soil (typical of agricultural fields), the best approach would be to attempt to deplete the surface fraction of the seedbank through repeated shallow cultivation. In Nebraska, shallow disking (10-cm depth) of former crop land helped incorporate plant residues, allowed enough cover to protect against wind and water erosion, and reduced perennial weeds enough to allow good emergence of native seedlings compared to the untilled treatments (King et al. 1989). On the other hand, if seeds are found predominantly on the soil surface (typical of old fields), then Mohler (1993) suggests that deep plowing with minimal soil disturbance thereafter will produce the best results. Deep plowing inverts the soil so weed seeds are placed too deep to germinate (Bond and Grundy 2001). Some top soils however, such as in Oregon, may be too shallow to plow because it brings the clay and mineral layer to the surface, which is a poor substrate for seed germination and plant growth (J. Krueger, pers. comm. 2004).

<u>Nighttime tilling</u> The use of nighttime tilling to restore weedy fields to native prairie may be of value, especially as a final tilling prior to sowing, because light can be a germination cue for some seeds (Gallagher and Cardina 1998). This could potentially reduce weed competition during the critical stage of native seedling emergence. Daytime tilling in western Oregon increased weed seed germination (mainly redroot pigweed and nightshade) between 70 percent and 400 percent above the levels for nighttime tilling (Scopel et al. 1994, Botto et al. 1998). Often this response depends on the weed species, type of tillage, and time of year. Botto et al. (1998) found that daytime tilling with a moldboard plow in Argentina led to a 200 percent increase in germination over nighttime tilling,

whereas tilling with a chisel plow produced no difference in germination rates. In general, it appears that monocots and perennials are less responsive to nighttime tilling than annuals. In western Oregon, nighttime tilling of an upland pasture field being restored to native prairie was ineffective at reducing the cover of mostly introduced perennial grasses and forbs including, colonial bentgrass *(Agrostis capillaris*), sweet vernal grass (*Anthoxanthum odoratumI*), velvet-grass (*Holcus lanatus*), sheep sorrel (*Rumex acetosella*) and cat's ear (*Hypochaeris radicata*) (Fitzpatrick 2003). Thus, nighttime tilling will probably be beneficial in only those situations where the primary weeds are annual dicots and grasses. This might occur when converting former cropland to native prairie, where frequent cultivation often leads to an increase in annual weeds, or in California where old fields have become dominated by non-native annual grasses and forbs. Before trying this technique on a large scale it should be tested during different seasons and against weeds present at the site.

Herbicides

There are a number of herbicides, both conventional and natural, that can reduce weedy vegetation. Nonspecific herbicides, such as glyphosate, can reduce established non-native grasses and forbs prior to tilling. Broadleaf-specific, grass-specific, and post-emergent herbicides can help reduce persistent weeds after seeding. Although a single use of herbicides may control weeds for a season, multiple treatments are generally more effective.

<u>Conventional herbicides</u> Herbicides often only provide short-term control of weeds. A study in Washington found that glyphosate reduced weed biomass, consisting mainly of velvet grass (*Holcus lanatus*), tall fescue (*Festuca arundinacia*), Kentucky bluegrass (*Poa pratensis*) and redtop (*Agrostis alba*) to about 40 g/m^2 after the first season, but by the third season weed biomass had increased to about 480 g/m^2 (Ewing 2002). Although herbicides may provide only short-term control, it may be sufficient to allow native plants to emerge and become established. In a study where blue grama was seeded into a crested wheatgrass field in Saskatchewan, applying glyphosate greatly increased establishment rates of blue grama compared to the control (Bakker et al. 1997). Similarly, in a nearby study, spraying glyphosate significantly reduced cover of *Agropyron cristatum* and *Bromus inermis*, resulting in a 20-fold increase in native seedling density four months after the herbicide application (Wilson and Gerry 1995). The authors suggest that a follow-up treatment of glyphosate using a wick applicator will be necessary to control the introduced grasses that reemerge. A wick applicator is a device that wipes rather than sprays an herbicide onto the tops of taller weeds thus reducing damage to slower growing and shorter native plants.

Some workers have found that applying an herbicide over a number of years to the same field can reduce the weeds and seed bank (Morgan 1997), while others have not. Researchers in southwest Saskatchewan, found that applying glyphosate annually to an *Agropyron cristatum*-dominated field for four seasons did not lead to its decline, probably because intraspecific competition decreased which allowed seed production to increase (Ambrose and Wilson 2003).

Burning prior to spraying herbicides can reduce thatch and weed seeds, and thus allow better contact of herbicides with new weed growth (Morgan 1997, Grilz and Romo 1995). In Saskatchewan, spraying glyphosate after spring burning eliminated *Bromus inermis* compared to a 76 percent and 50 percent reduction in density for fall burning and no burning treatments, respectively (Grilz and Romo 1995). Furthermore, the glyphosate treatment after spring burning continued to provide excellent control (98 percent) even after 15 months. This may have been because smooth brome did not produce a persistent seed bank and burning destroyed most surface seeds from the previous crop. Combining burning with an herbicide may be especially critical when there is an abundant weed seed crop on the soil surface. A combination treatment where a field is sprayed with an herbicide, burned, then resprayed is highly effective in many situations (R. Bowen, pers. comm. 2004).

Sometimes using a nonspecific herbicide such as glyphosate, along with a selective, post-emergent herbicide like imazapic (which does not affect certain broadleaf plants and many grasses) can be more effective at reducing weed cover and increasing native species (Beran et al. 1999, Cox 2003). In Kentucky, spraying tall fescue (85-98 percent cover) with glyphosate reduced cover to less than 12 percent in most treatments, and a follow-up application of imazapic two years later eliminated or reduced residual tall fescue from most of the plots and allowed seeded native grass cover to increase, on average, from 30 percent to 70 percent (Washburn et al. 2002). Since many forbs and some grasses may be sensitive to imazapic, caution is advised when using it in restoration projects (Cox 2003).

If a prairie is planted in a two step process, with grasses sown the first year and forbs the second, then a broadleaf herbicide such as 2,4-D can be used to control persistent weedy forbs (Stromberg and Kephart 1996, Bugg et al. 1997, Brown and Bugg 2001). This two-step process can also be reversed, with all non-grasses sown in the first year (following several glyphosate applications), followed by a spring, summer, or early fall application of a grass-specific herbicide such as Post, followed by a planting of grasses (E. Wold, pers. comm. 2004). The challenge with seeding grasses first is finding an effective method of introducing forbs into established grasses. Bugg and Brown (2001) found that sowing native seeds in California without any treatment led to very poor establishment of forbs, while transplanting small plants was more successful. Light disking of an established grass field may be another approach to allow interseeding of native forbs. In Illinois, Dovel et al. (1990) found that the establishment and survival rates of a native legume, Illinois bundleflower (*Desmanthus illinoensis*), interseeded into a dense stand of a non-native bunchgrass (*Panicum coloratum*), was higher after light disking than either the control or two herbicide treatments. Mowing, burning and grazing may also be beneficial for seeding in forbs into dense stands of grasses. See Jones and Hayes (1999) and Howe (1999) in the Short-Term Management section of this paper for more details.

One disadvantage of using herbicides is that the microflora and fauna in the soil may be compromised. Some laboratory studies have shown that herbicides such as glyphosate can reduce nitrogen-fixing nodules on clover and mycorrhizae on conifers (Cox 1998). Since below-ground processes are vitally important to the health and productivity of prairies (Miller 1997), caution should be used when applying herbicides.

<u>Organic herbicides</u> Given that conventional herbicides may compromise the soil food web and many federal, state and local regulations preclude their use, more acceptable alternatives are often needed. Some broad-spectrum natural herbicides are becoming available that may provide some level of weed control. Two examples are corn gluten and acetic acid. Chinery (2002) found that a 20 percent acetic acid formula exerted a 66 percent control compared to 95 percent control by glyphosate after 13 weeks against a variety of annual and perennial grasses and forbs (e.g., quackgrass, crabgrass, dandelion, Kentucky bluegrass). Applying the 20 percent acetic acid herbicide three times increased control to 81 percent. Since so few scientific studies have been done on this relatively new herbicide, little is known about its efficacy on other weeds and its effect (especially pH) on microorganisms in the soil.

Corn gluten, a pre-emergent herbicide that is 10 percent nitrogen by weight (often referred to as a natural weed and feed product), kills monocot and dicot weed seedlings by inhibiting their root development and growth. Plants with mature roots are not affected. Liu and Christians (1997), in a petri-dish bioassay, found that adding corn gluten produced a greater than 80 percent reduction in germination of creeping bentgrass. The concern with using corn gluten herbicide for prairie restorations is that some non-native species may be tolerant and consequently may increase in cover due to the increased nitrogen. In a greenhouse study, three out of four perennial grasses (*Anthoxanthum odoratum*, *Festuca arundinacea*, *Phalaris aquatica*) tested had germination rates higher than 55 percent relative to the control (ranging from 55 percent to 93 percent). In addition, the grasses that germinated with corn gluten showed more growth compared to the control, probably due to nitrogen.

Nonetheless, corn gluten was quite successful at reducing germination rates of some non-native forbs. Six out of eight non-native forbs tested had germination rates averaging less than 4 percent (*Leucanthemum vulgare*, *Senecio jacobaea*, *Mentha pulegium*, *Cirsium vulgare*, *Leontodon taraxacoides* and *Dipsacus sylvestris*) compared to the control (unpublished data, Fitzpatrick 1998). Combining corn gluten with a carbon source, such as sawdust, could help to reduce the nitrogen that is released by the herbicide.

The challenges associated with using natural herbicides include high costs, lack of availability in large quantities and insufficient knowledge about efficacy and application rates. Often the best sources concerning natural herbicides are local organic and sustainable growers and University extension agents. With additional research and use of these products, more information will become available in the future.

Thermal weed control

The primary thermal weed control techniques discussed in this paper include flame weeders (also called infrared burners) and solarization. Flame weeders use propane to produce high temperatures (combustion temperatures can reach approximately 540-1090º C) that kill vegetation by rupturing plant cells exposed to the heat. Solarization is a weed control method that relies on covering moist soil with clear plastic sheeting for a period of several months during the summer. These techniques can be effective at reducing both existing weeds and the weed seed bank. Although most practitioners have relied on broadcast burning to restore prairies, flame weeders might provide an alternative when field conditions are unsuitable (e.g., lack of sufficient fuel or too green) or where higher temperatures might provide better weed control. Up to now, solarization has seen limited use in prairie restorations mainly because covering large areas with plastic sheeting often requires specialized machinery. Recent studies suggest that this technique may be effective at reducing weed seeds and weeds, and therefore may hold promise for smaller restoration projects or when herbicides are not an option.

<u>Flame weeders</u> Flame weeders vary in design. While most flamers have open burners, more advanced ones have insulated covers and misters that produce infrared heat, steam and turbulent hot air (Ascard 1998). Flame weeding is becoming more widely used, especially in organic farming, because it can substitute for chemical weed control. Models describing the response to flaming show plant size has a large effect on dose requirement, while density is less important (Ascard 1994). Weed seedlings are readily killed by a single treatment whereas larger more established weeds are only top-killed and

often require multiple treatments (Bond and Grundy 2001). One study found that flamers are more effective against dicots than grasses, probably due to the grass's protective sheaths (Bond and Grundy 2001). However, field observations in Oregon have found that *Hypochaeris radicata* increased after flaming, possibly due to protective hairs on their leaves and their ability to quickly colonize open soil (T. Taylor, pers. comm. 2004). Many of the studies on vegetation responses to broadcast burning may be relevant to flaming.

Perhaps the best use of weed flamers is for killing surface weed seeds and small weed seedlings that emerge after tilling. Typically herbicides or cultivation are used to kill this flush of new seedlings. However, flamers may be a superior method because they emit no harmful chemicals and create very little disturbance that might stimulate additional weed emergence (Stromberg and Kephart 1996). Flamers have also been used as a post-seeding treatment (when seeds are drilled), timed so that flaming occurs before native seeds germinate (Bond and Grundy 2001). Using flamers in a post-seeding application would need to be tried first to ensure that temperatures are not lethal to the native seeds. In Oregon in an upland field, researchers using an infrared burner after tilling and again prior to seeding, found it to be more effective than a single application of glyphosate at reducing introduced forbs (*Rumex acetosella, Hypochaeris radicata, Leontodon taraxacoidies*) and an annual introduced grass (*Vulpia bromoides*). In addition, it was as effective as glyphosate in helping to establish native plants (Fitzpatrick 2003).

Weed flaming could also be used to replace broadcast burning in situations where the vegetation is too green (in the spring) or where fine fuels are insufficient to carry a fire. Stromberg and Kephart (1996) used propane-fired burners in California to kill emerging non-natives early in the spring when there were insufficient fuels. Combining burning with an herbicide may be especially critical when there is a need to kill weed seeds prior to tilling. After seeds are buried, they can persist for long periods of time depending on the species. Grilz and Romo (1995) in Saskatchewan found that applying an herbicide after a spring broadcast burn was more effective at reducing non-native grasses (e.g., *Bromus inermis*) than herbicide alone, and there was very little increase in the non-native grass, even after 15 months. Weed flaming could probably have been substituted for broadcast burning in this case, if conditions were not ideal, and if burning was considered critical for reducing the surface weed seed.

<u>Solarization</u> During solarization, heat created by the sun and trapped beneath the plastic can reach temperatures greater than 65° C, which can kill weeds and weed seeds near the soil surface (Horowitz et al. 1983, Standifer et al. 1984, Bainbridge 1990, Egley 1990, Wilson et al. 1994, Bond

and Grundy 2001, Wilson et al. 2004). Solarization is most effective if the ground is tilled, the soil is moist prior to plastic installation, and the site has extended sunny and warm conditions. Moist soil conducts heat better than dry soil and it promotes seeds to germinate, which are then killed by the high heat (Egley 1990). Egley (1990) also found that seeds are killed at lower temperatures (50° C) in moist soil than dry soil (70° C).

While solarization is effective at reducing weeds (Wilson et al. 2004), it may provide only a short-term (one season) reduction in weed cover. In a western Oregon wetland prairie, Wilson et al. (2004), found that solarization reduced the emergence of dicots, and seeds of *Agrostis capillaris* and *Hypochaeris radicata* compared to the control. Weed cover was also reduced in solarized plots (34 percent) compared to the control (60 percent), but by the second season non-native plant cover was similar to the control. Similarly, solarization in experimental plots at a nearby nature preserve was more successful than tilling, flaming and herbicide at creating bare ground, but by the second season the treatment effect had disappeared and consequently did little to promote the establishment of sown native species (Fitzpatrick 2003).

Although solarization has been used mostly in experimental and small restoration projects, its potential is much greater if commercial agricultural machinery is used to apply the plastic. For example, growers can cover many hectares with plastic in preparation for growing strawberries and in the process of fumigating soils (Hartz et al. 1993). One drawback to doing solarization on larger scales is that the plastic sheeting often has to be sent to a landfill, although there has been a limited effort at recycling. Another alternative might be to use a biodegradable plastic that could be plowed into the ground after its use. At this time biodegradable plastic sheeting is still too costly and experimental, but in the future it might be produced in large enough quantities to make it feasible.

Combining techniques

Some practitioners and researchers have found that combining treatments that target the different life stages of plants (seeds, seedlings, adults) and doing treatments multiple times over several seasons can reduce non-natives and enhance the establishment of natives better than doing single one-time treatments (Stromberg and Kephart 1996, Morgan 1997, Howe 1999, Kurtz 2001, Wilson 2002). To reduce non-native annuals on fallowed agricultural land in California, Stromberg and Kephart (1996) found that a combination of tilling, using a variety of methods (rippers, disc harrow, spike-toothed harrow) up to four times to kill existing vegetation and numerous flushes of weeds, and spraying glyphosate prior to planting natives, led to high establishment rates of native grasses and a significant reduction of the non-native annual grasses. They also suggest a combination of treatments to establish native grasses in upland sites in California, including dry-season burning, late winter herbicide application, intensive and short-duration grazing or mowing in late winter and early spring. Morgan (1997) advocates a variety of treatment techniques to establish native prairies in the Midwest. The treatments include burning in late fall or early spring to remove the litter and surface seed bank; applying several applications of herbicides (specific and nonspecific) at three or four week intervals once the vegetation has regrown; removing the remaining vegetation by mowing or fire; cultivating several times to prepare a seedbed and doing a final herbicide treatment prior to seeding native prairie plants.

In Wisconsin, researchers worked the land over a three-year period to reduce weeds and ensure good establishment of natives (Howe 1999). During the first year in the fall they applied glyphosate to the non-native grasses *Bromus inernis, Poa pratensis*, and *Agropyron repens* and followed that with a burn and plowing. The next summer and following spring the field was disked and spot sprayed to further reduce the weedy grasses. Native seeds were then planted. Two years later they found that 95 percent of the cover consisted of the dominant native grass.

IMPROVING THE COMPETITIVE ENVIRONMENT FOR NATIVES

It is often assumed that non-native species are competitively superior to native species. However, recent studies exploring the competitive abilities of non-native and native species have found mixed results (Bakker and Wilson 2001, Davis 2001, Seabloom et al. 2003a, Seabloom et al. 2003b), probably because of the great diversity of plants and their life-history strategies within these two groupings. Also, many fields formally used as agriculture or pasture land may have higher than normal nitrogen levels which may be utilized by non-natives more extensively than natives, thereby increasing their competitive ability (Davis 2001). In Saskatchewan, a study looking at the competitive responses of a C_4 native grass, *Bouteloua gracilis* and a C_3 introduced grass, *Agropyron cristatum*, found that competition led to a 60 percent decline in *Bouteloua* growth compared to only 33 percent decline for *Agropyron* (Bakker and Wilson 2001). The authors suggest that this result indicates *Agropyron* is better able to resist competitive suppression than *Bouteloua*. Other studies provide evidence that some native species are superior competitors to non-natives. In an Oregon wetland prairie, a study testing competition at the seedling stage found that most of the non-native grasses (*Anthoxanthum odoratum, Holcus lanatus, Phalaris arundinacea*) were more suppressed by competition than were the native grasses (*Beckmannia syzigachne, Danthonia californica,* *Deschampsia cespitosa*) (Davis 2001). The author suggests that the reason non-native species are so successful in degraded prairies is because many invasive species are superior colonizers and rely on large seed production and efficient seed dispersal to occupy disturbed areas. Similarly, a seed addition study in California, found that after correcting for seed limitation, native perennial grasses were able to reduce the abundance and fecundity of the non-native annual grasses (Seabloom et al. 2003b). The authors suggest that past disturbances coupled with inadequate seed dispersal and seed limitation of native perennial grasses has led to the dominance of non-native annual grasses in California habitats that were formally dominated by native perennial grasses.

Reducing soil nitrogen levels through carbon addition

Many degraded and abandoned fields that are slated for restoration may have elevated levels of nitrogen because they have been fertilized regularly and atmospheric nitrogen deposition has increased (Collins et al. 1998). Additionally, fields that are dominated by introduced rhizomatous grasses may promote higher levels of nitrogen mineralization than native bunch grasses (Wedin and Tilman 1990, 1996, Davis 2001), which can further increase nitrogen levels. Since non-native species are often fast-growing and nitrophilic, decreasing nitrogen levels can potentially help promote native species over non-natives.

One method of reducing nitrogen in the soil is to add a carbon source such as sugar or sawdust. This stimulates soil microbes to utilize nitrogen, thus making it unavailable for plants. Adding a more recalcitrant form of carbon, such as sawdust or straw, provides a more sustained level of carbon than sugar. The results from carbon addition experiments have been mixed. Some carbon addition experiments have shown limited or no success (Wilson and Gerry 1995, Seastedt et al. 1996, Schultz 2001, Corbin and D'Antonio 2004), or short-term nitrogen reduction (Morghan and Seastedt 1999). Other studies provide evidence that carbon addition at higher levels can reduce weeds and promote natives (Morgan 1994, Davis 2001, Blumenthal et al. 2003).

Many of the carbon addition experiments may have failed because they did not add enough carbon. When Schultz (2001) added 650 g/m^2 of sugar to a field in Oregon and Wilson and Gerry (1995) added 400 g/m^2 of sawdust to a field in Saskatchewan over a period of three years, there was no effect on either non-native or native species. In California, Corbin and D'Antonio (2004) found that adding 200 g/m^2 of sawdust, six times over a period of 18 months, had no effect on reducing nitrogen or production of non-native annuals or perennials. The addition of sawdust did however, lead to a slight increase in growth of natives during the first year, but by the second year there was no difference between sawdust addition and the control. The authors suggest that the soil nitrogen may have been too high in relation to the amount of sawdust added, and that adding more sawdust may have produced better results.

In Minnesota, when carbon ranging from 84 to 3346 g/m^2 (94 percent sawdust, 6 percent sugar) was added to the soil, nitrate levels decreased at all levels of carbon. At the highest level of carbon addition, weed biomass decreased by 54 percent (most of which were annual weeds), and prairie species biomass increased eight-fold compared to the control (Blumenthal et al. 2003). The authors found that overall, about 1000 g/m^2 of carbon were necessary to reduce weed biomass and 1500g/m^2 were necessary to promote native plants. It is important to note that the weeds in this study were sown as seed and did not grow from established plants. For this reason, and the fact that the perennial weeds increased with carbon addition, the authors caution that established perennial weeds, especially those that are deep rooted, may not be affected by carbon amendments. Furthermore they suggest that the practical use of carbon in a restoration project may depend on the existing nitrogen levels. If nitrogen levels are too high then it may require an exorbitant amount of carbon to be beneficial.

Although most carbon addition studies have focused on upland or semi-arid habitats, at least one study has demonstrated that carbon addition in a wetland prairie can suppress weeds and benefit native plant establishment. When about 2000g/m^2 of sawdust and sugar was added in equal amounts to an Oregon weedy wetland prairie, dominated by mostly non-native perennial plants (*Holcus lanatus, Agrostis capillaris* and *Hypochaeris radicata*), there was a significant decrease in nitrate and ammonium levels and biomass of non-native grasses (Davis 2001). Although there was no effect on either the non-native or native forbs, it did lead to an increase in two of the three native grasses that were sown (*Deschampsia cespitosa* and *Bechmannia syzigachne*, but not *Hordeum brachyantherum*).

The practicality of carbon addition will depend on nitrogen levels at a particular site, the native and non-native species involved, and the cost of obtaining the carbon and incorporating it into the soil. Before choosing this restoration technique it would be prudent to test soil nitrogen levels to see if carbon is a practical approach. Since carbon addition does not seem to reduce many non-native forbs, other control measures for these species would need to be considered.

Mycorrhizal fungi

Mycorrhizal fungi are symbionts that infect the roots of approximately 80 percent of all terrestrial plants, and provide their host with soil resources in exchange for photosynthate (Van der Heijden et al. 1998, Klironomos 2003). Mycorrhizae, with their extensive fungal filaments or hyphae, increase the capture and uptake of critical nutrients for plants, especially phosphorous, but also nitrogen and other minerals from the soil, particularly under low fertility conditions (Hetrick et al. 1994, Allen 1996, Johnson et al. 1997, Van der Heijden et al. 1998). They can also increase drought tolerance, inhibit plant diseases and improve soil structure by increasing soil aggregation through their hyphae and the release of polysaccharides (Zajicek et al. 1987a, Johnson et al. 1997). The most common mycorrhizae type, the arbuscular mycorrhizae fungi (AMF), predominates in grasses, forbs, bryophytes and tropical trees. AMF are generally mutualistic, but under certain conditions they can become parasitic. This can occur when soils are highly fertilized, when plants are under low light conditions, or if a plant becomes infected with an unsuitable fungal isolate or genotype (Johnson et al. 1997).

Mycorrhizae are generally more abundant in undisturbed natural areas than areas associated with disturbance or human activity such as fire, tilling, compaction, soil removal, land clearing, strip mining, weed invasion, and pesticide use (Reeves et al. 1979, Waaland and Allen 1987, Baltruschat and Dehne 1988, Hetrick et al. 1992, Douds et al. 1993, Allen 1996, Haselwandter 1997, Douds and Millner 1999, Jorden et al. 2000, Amaranthus and Steinfeld 2003). Mycorrhizal fungal communities may show an increase in infectivity and spore count and diversity over time during old field succession. Johnson et al. (1991) found fallow and rye fields tend to have lower densities of infected propagules compared to older fields, and species diversity increased primarily due to a decrease in one species of mycorrhizae. Although soil solarization creates disturbance and is used to kill pathogens and weeds, it may actually be beneficial to mycorrhizae colonization (Nair et al. 1990). A study investigating the effect of solarization on mycorrhizae colonization in crops found no adverse effects on the native mycorrhizae (Afek et al. 1991). The authors suggest that solarization may actually promote mycorrhizae colonization by killing microorganisms that compete with mycorrhizal fungi. Ingham and Wilson (1999) found mycorrhizae spore count to be 3.5 fold higher in solarized than in unmanipulated plots.

Fire, which is often used to maintain and enhance prairies, can influence mycorrhizal fungi diversity and spore abundance (Rashid et al. 1997, Eom et al. 1999). In a Kansas tallgrass prairie, Eom et al. (1999) found that 10 years of annual spring burning led to an increase in AM fungal species, a decline in the number of spores, but no significant effect on fungal colonization of roots. Similarly, in an Illinois sand prairie, Dhillion et al. (1988) and Dhillion and Anderson (1993) found mycorrhizal spore counts to be lower in burned plots compared to unburned plots. The authors suggest that mycorrhizal fungi are probably not directly affected by fire because soil is a good insulator. The changes in spore count are more likely due to changes in the host plant in response to fire, such as root growth.

A plant's dependence on mycorrhizae may depend on plant phenology, root morphology or type of habitat (Hetrick et al. 1988, Hetrick et al. 1992). Mycorrhizae are more commonly present in warm-season than cool-season grasses, possibly because the cooler soils may lower the metabolic rate of the fungal symbiont (Hetrick et al. 1992). There is also evidence that root morphology may play an important role in whether a plant has associations with mycorrhizae. Studies have shown that warm-season grasses and forbs have roots that are coarser and less branching than cool-season grasses and are more frequently infected with mycorrhizae (Hetrick et al. 1988). It is hypothesized that cool-season grasses developed more fibrous roots because mycorrhizae were ineffective at transporting nutrients in cool environments. In general, plants in undisturbed habitats are highly mycorrhizal, plants in mildly disturbed sites are facultative mycotrophs, while plants in highly disturbed sites are nonmycotrophic (Reeves et al. 1979, Hetrick et al. 1992, Haselwandter 1997, Greipsson and El-Mayas 2000).

<u>Mycorrhizae in wetland plants</u> Until recently it was assumed that mycorrhizae were uncommon or nonexistent in wetland plants because of their inability to survive in anoxic soils. However, evidence is accumulating that mycorrhizae can exist in wetland ecosystems (Aziz et al. 1995, Wetzel and van der Valk 1996, Cooke and Lefor 1998, Turner and Friese 1998, Ingham and Wilson 1999, Miller 2000, Turner et al. 2000, Bauer et al. 2003). In a recent study in northern Indiana, it was determined that mycorrhizae were present across all hydrologic zones in two restored and one reference wetland (Bauer et al. 2003). Similarly, Ingham and Wilson (1999) in western Oregon found five different wetland habitats that varied in land use intensity and restoration efforts, were colonized with mycorrhizae, averaging between 58 percent and 92 percent. Most of these sites were being restored using tilling, herbicide and solarization techniques, while the last site was an abandoned pasture consisting of about 45 percent native forbs and grasses. The six wet prairie plant species that were investigated were all colonized with mycorrhizae, averaging from 54 percent for *Deschampsia cespitosa* to 96 percent for *Microseris laciniata*. It is interesting to note that the abandoned pasture had the lowest rate of colonization, averaging 73 percent compared to greater than 85 percent for all other habitats.

Cooke and Lefor (1998) also found as many as 89 species of plants from a variety of Connecticut freshwater wetland and transition zone habitats to be colonized by mycorrhizae. The authors suggest that mycorrhizae may be able to exist under low oxygen conditions because they take advantage of the aerenchyma structure of wetland plants that allows diffusion of oxygen to the roots from above-ground plant parts. Although many species of wetland plants are colonized by mycorrhizal fungi, the level of infection may decline with higher water levels. In a greenhouse study looking at the effect of flooding on mycorrhizal colonization of two semi-aquatic grasses in South Carolina, there was a decline in mycorrhizal colonization with rising water level (Miller and Sharitz 2000). It was also found that if the grass roots were colonized prior to flooding then the mycorrhizae remained viable, at least over the course of a few months.

Mycorrhizae benefit plants Prairie studies have shown that seeds that were inoculated, or plants that were colonized, with mycorrhizae can have increased seedling survival and emergence (Grime et al. 1987, Gange et al. 1990, Richter and Stutz 2002, Amaranthus and Steinfeld 2003), growth (Zajicek et al. 1987b, Greipsson and El-Mayas 2000), productivity (Zajicek et al. 1987b, Wilson and Hartnett 1997) and survivorship (Wilson and Hartnett 1997, Richter and Stutz 2002). Studies have also shown that mycorrhizae may or may not enhance plant species diversity (Gange et al. 1990, Moora and Zobel 1996). In Kansas, plant species diversity (mainly species evenness) increased when mycorrhizae were suppressed and the dominant plants were mycorrhizae-dependent, (e.g., C_4 warm-season grasses), probably because the subordinate mycotrophic C_3 forbs and grasses became relatively more abundant (Wilson and Hartnett 1997, Hartnett and Wilson 1999). In contrast, Grime et al. (1987) in a laboratory study found that plant diversity increased with the addition of mycorrhizae (*Glomus constrictum*) when the dominant species in the community were cool-season grasses and nonmycorrhizal-dependent. The authors hypothesize that plant species diversity may be enhanced through a process where canopy dominants contribute photosynthetic assimilate to subdominant species through a common mycorrhizal network.

The influence of mycorrhizae on plant sexual reproduction has been mixed (Zajicek et al. 1987b, Wilson and Hartnett 1997, Smith et al. 1998). Wilson and Hartnett (1997) found that when mycorrhizae were suppressed by a fungicide, reproductive effort of warm-season grasses declined while vegetative biomass increased. In contrast, Zajicek et al. (1987b) found that reproductive effort (i.e., inflorescences per plant) of native prairie forbs increased when plants were inoculated with mycorrhizae.

Mycorrhizae colonization and inoculation Since disturbed or degraded sites may have fewer mycorrhizae, the success or rate of restoration may be enhanced by increasing the level of colonization and diversity of mycorrhizae at a site (Haselwandter 1997, Streitwolf-Engel et al. 1997, Richter and Stutz 2002, Amaranthus and Steinfeld 2003, Klironomos 2003). Other workers have documented fairly rapid mycorrhizal colonization of restoration sites from surrounding areas (Johnson and McGraw

1988, Aziz et al. 1995, Miller 1997, Ingham and Wilson 1999, Bauer et al. 2003). A study comparing mycorrhizae with a slow-release fertilizer at a denuded site in southwest Oregon found that native dune bent grass (*Agrostis pallens*) seeds inoculated with a common mycorrhizae (*Glomus intraradices*) had 100 percent survival compared to 26 percent survival for seedlings that were just fertilized (Amaranthus and Steinfeld 2003). Furthermore, the mycorrhizal-inoculated seedlings had significantly greater root biomass and foliar levels of phosphorous, potassium, calcium and sulfur compared to seedlings with fertilizer only. It has been suggested that natural inoculation rates may vary among ecosystems. For example, disturbed wetland ecosystems may be more rapidly re-inoculated by spores moving in surface water than drier upland ecosystems (Trevor Taylor, per. comm. 2004).

If artificial inoculation of mycorrhizae is to occur, it may be better to use a diverse and locally adapted mycorrhizae community, rather than a single species, or mycorrhizae from a commercial source that may not contain local strains of mycorrhizae. In Iceland, when seeds of the Iceland sand dune grass, lymegrass (*Leymus arenarius*), were inoculated with mycorrhizae and grown in pots for 60 days it was found that plants inoculated with an indigenous mycorrhizae inoculum had significantly higher growth compared to two commercial inocula (consisting of either three or one species of *Glomus*) or a control (Greipsson and El-Mayas 2000). The authors suggest an alternative method for mycorrhizae dispersal into restoration sites. Rather than relying on a large-scale production of inocula, which can be time consuming and costly, they suggest inoculating nursery grown plants with indigenous mycorrhizae and then out-planting these into the restoration site. These then can act as a source of inoculum and disperse to the rest of the site (Greipsson and El-Mayas 2000). Smith et al. (1998) in Minnesota found that inoculating native seed with about 20 species of mycorrhizae, obtained from a native undisturbed prairie, resulted in a significantly greater percentage of roots colonized by mycorrhizae and percent cover of native planted grasses than the control. The authors hypothesize that the increased native plant cover may have resulted from the mycorrhizae increasing the competitive ability of these grasses. A greenhouse study by van der Heijden et al. (1998) found that plant biodiversity and ecosystem productivity increased as the species richness of mycorrhizae increased, suggesting that inoculating with a diverse community of mycorrhizae rather than a single species may be important.

Deciding which species of plant to use as a nursery crop for indigenous mycorrhizae may be a challenge. Noyd et al. (1995) tested the suitability of three native grasses to be infected with mycorrhizae and found that one species produced five times longer mycorrhizae-infected roots than the other two species, making this species a good candidate for out-planting to help increase propagule density of mycorrhizae.

SEEDING AND PLANTING

There are a number of recommended methods for collecting seeds, choosing seed densities and seed mixes, and sowing seeds, all which may vary depending on the goals and location of the restoration project. I limit my discussion here to seeding and planting methods and designing seed mixes. For a more complete discussion of seeding and planting techniques see Stromberg and Kephart (1996), Packard and Mutel (1997), Kurtz (2001), and Wilson (2002).

<u>Seeding method</u> Both broadcasting and drilling have shown to be effective under different circumstances. Using a seed drill leads to more efficient use of limited seed; it is recommended that twice as much seed be sown when broadcasting (Morgan 1997). Drilling may also lead to higher emergence rate. In Saskatchewan, Ambrose and Wilson (2003) found that under field conditions, 80 percent of seeds buried 1 cm below the soil surface emerged compared to 20 percent for surface sown seed. The opposite was found for seeds emerging in the greenhouse where the soil was kept moist. The authors suggest burying seeds may protect them from drying out; however, using a heavy roller or light harrowing to obtain close seed-soil contact may also prevent the seeds from drying out (Stromberg and Kephart 1996). Other researchers have found that broadcasting may lead to higher survivorship rates than drilling (Bakker et al. 1997, Bakker et al. 2003). Bakker et al. (2003) found that drilling and broadcasting produced similar establishment rates, but survivorship was nearly three times greater for broadcasting. The authors hypothesize that seedlings in drilled rows experience much higher competition than seedlings that emerged from broadcast plots. They recommend broadcasting over drilling because "it allows the formation of plant-induced heterogeneity." One method that can reduce the aesthetic concerns of drilling is to "cross-drill". This is where seeds are drilled using two passes, where one pass is perpendicular to the other pass. This method may also reduce the bare ground that is available for non-natives to reinvade and lessen competition between forbs and grasses if grasses are drilled one direction and forbs the other direction (L. Boyer, pers. comm. 2002). Other workers suggest that a combination of drilling and hand broadcasting may be necessary to ensure that seeds needing light are accommodated (J. Jancaitis, pers. comm. 2003). The success of either method in the end may depend on rainfall patterns in a particular year, and whether the site tends to dry out quickly.

An alternative option is to use a no-till drill. A no-till drill uses as series of smaller disks, followed by a seeding tube to open the ground lightly and immediately prior to seeding. The no-till drill does not require that site be tilled or disked prior to seeding. However, too much standing vegetation or thatch may reduce the effectiveness of the no-till method. A no-till drill can be advantageous because it reduces time and effort to prepare a site, reduces moisture loss because the sod acts as a mulch, reduces loss of mycorrhizae, decreases weeds because seeds are left buried and reduces loss of physical characteristics of the soil (Morgan 1997). Burning allows restoration practitioners to seed or plant an area with fewer disturbances to the seed bank when combined with using a no-till drill or a broadcaster.

Seed mixes Studies have shown that many sites being restored to native prairie and wetlands are seed limited due to degraded seed bank and geographical isolation, making it difficult to restore a diverse native plant community (Tilman 1997, Turnbull et al. 2000, Seabloom and Van der Valk 2003, Clark and Wilson 2003, Seabloom et al. 2003a, Seabloom et al. 2003b, Foster and Tillman 2003). Furthermore, seed limitation tends to be more critical for early successional habitats and early successional species (Turnbull et al. 2000). Some practitioners suggest that the best way to establish a native prairie is to first sow high seeding rates of a few native grasses and pioneer forbs that compete well against non-natives (Mlot 1990, Packard and Mutel 1997). It is during the second stage that the more conservative species (species that prosper in a more successionally advanced community) or prairie obligates are then planted in order to increase diversity. For example, to establish native plants along roadsides, Tyser et al. (1998) suggests sowing a low diversity seed mix consisting mainly of native rhizomatous grasses that can tolerate disturbance and establish quickly to stabilize soil conditions.

In contrast, Weber (1999) advocates a different approach to seeding prairies. He recommends sowing, at the very start, a high diverse grass and forb seed mix that limits the number of aggressive native species. He suggests that it is easier to add in aggressive species later than to add in the conservative species to an established planting. Weber (1999) considers competition, not slow germination, to be the main factor reducing the success of the conservative obligate prairie species. He suggests that limiting some of the aggressive native species reduces the swamping effect and gives the slower growing prairie plants a chance to survive.

In Oregon wetland prairies, researchers have identified certain species that may be good candidates to include in a seed mix (Wilson et al. 2004). For instance, *Plagiobothrys figuratus* seeds were found to be very viable with high emergence rates, which allowed for high cover during the first year. These qualities could help reduce and slow weed invasion. By the second year, cover diminished considerably, allowing other slower growing native species such as *Deshampsia cespitosa* to grow and become effectively established.

Another seed mix approach is to combine seeds into distinct associations (mosaic seeding) so it better mimics a natural prairie (Morgan 1997, Weber 1999). This method can also reduce seed failure due to incompatibility with site conditions; seeding plants on hilly sites that are adapted to drier conditions and mesic plants to mid-slope sites will probably lead to higher survivorship rates. Site matching or micro-site planting within an overall site can be very important and critical for success (R. Bowen, pers. comm. 2004).

In cases where seeds are scarce (due to species rarity or a bad seed year) or species do not establish well from seed, then planting bulbs, plugs, or bare-root stock may be the most effective approach (Stromberg and Kephart 1996, E. Wold, pers. comm. 2004). In Washington, plugs of *Festuca idahoensis* var *roemeri* were successfully raised from seed and planted out in plots (Ewing 2002). In an Oregon upland prairie *Camassia quamash* was successfully planted as bulbs and *Lupinus sulphureus kincaidii,* an endangered forb, was successfully planted as plugs (Schultz 2001). The *L. kincaidii* in this study was originally planted as seed (10,000 seed) without much success, less than 10 percent survived compared to a 50 percent-90 percent survival for plugs, during the first year. In California where the forbs *Asclepias fascicularis* and *Sisyrinchium bellum* were introduced into established perennial grasses, it was found that seeded forbs had reduced growth and were less successful than transplants (Brown and Bugg 2001).

Since each site and region varies in terms of aggressive non-natives, native seed mixes will need to be tailored to fit the conditions of each site. If a site has an abundance of aggressive non-native perennial plants and seeds, then it may be necessary to design a seed mix with more aggressive natives to effectively compete with the non-natives.

POST-SEEDING MANAGEMENT

Both short-term and long-term post-planting management may be critical to the successful establishment of native prairies (Stromberg and Kephart 1996, Packard and Mutel 1997, Kurtz 2001). Since non-natives are likely to re-sprout from vegetative parts that were not killed and emerge from seeds in the soil and seed rain from surrounding weed infestations, many practitioners and researchers strongly suggest follow up weed control measures. There may also be a need for supplemental sowing or planting for those species that failed to become established. Furthermore, the long-term maintenance of prairies to restore ecological processes and functions may require burning and grazing.

Short-term management

There are a number of short-term post-seeding management techniques that can improve the success of prairie plantings, including hand weeding, herbicide application, mowing, grazing and sowing additional seed. These techniques can help reduce the non-native plants that re-sprout or germinate from the seed bank and reduce weed seed production. These techniques can also reduce competition for light between non-natives and natives and enhance species diversity. Stromberg and Kephart (1996) in California experimented with different treatments to establish clean native grass fields for seed production and found that a combination of spring mowing, broadleaf herbicides and early green-season grazing were important for several years after seeding into a field that was dominated by annual non-native grasses.

Hand weeding In California, hand weeding of *Lolium multiflorum* was necessary during the first winter growing season in order to reduce its impact on native grass plugs (Stromberg and Kephart 1996). Hand weeding during the first two years has been found to be effective at significantly reducing non-natives after planting native wet prairies in western Oregon (T. Taylor, pers. comm. 2004). Solecki (1997) recommends hand pulling over herbicides to reduce invasives because of the potential for herbicides to do collateral damage to natives. It is best if weeds are pulled when the ground is still moist because roots will be more completely removed and less soil will be disturbed. The labor intensiveness of hand weeding limits its application at larger scales. However, self-propelled and tractor drawn platforms have been developed in Europe that can improve the efficiency of hand weeding (Turner 2000). This system allows up to eight workers to lie prone while hand weeding crops.

Herbicides Spot spraying or wick application of non-specific or specific herbicides is another method for reducing non-natives during the first and second years after prairie establishment. Workers in both the Midwest and California recommend a follow-up treatment of glyphosate using a wick applicator to control introduced grasses that reemerge after sowing native prairie species (Wilson and Gerry 1995, Stromberg and Kephart 1996, Morgan 1997). However, (R. Bowen, pers. comm. 2004) suggests that sometimes a wick application may not completely kill the target weeds due to insufficient coverage of the plant and that some amount of herbicide may reach the native flora if the wick height is not adjusted correctly or too much herbicide reaches the wick.

Mowing Well-timed post planting mowing can be critical for reducing weeds and establishing a high diversity prairie (Morgan 1997, Howe 1999, Jones and Hayes 1999, Wilson and

Clark 2001, Kurtz 2001). Mowing during the first season can reduce weed seed production, improve light conditions for small and slow growing native prairie seedlings and plants (Dyer et al. 1996, Collins et al. 1998, Weber 1999), and change competitive interactions between natives and non-natives (Howe 1999, Maron and Jefferies 2001). In California, Dyer et al. (1996) found that light availability early in the season may be more important than adequate moisture for the survival of the native bunchgrass *Nassella pulchra* seedlings. Timing of mowing treatments can make a difference when the object is to suppress dominant species. In Wisconsin, researchers looking for ways to increase the abundance of a subdominant tallgrass forb (*Zizia aurea*) found that mowing in August led to a doubling of the population of *Z. aurea*, when seeds were added to plots, compared to no change in population for a May mowing (Howe 1999). Howe suggested that the August mowing was late enough in the season that very little re-growth of the dominant vegetation occurred and the canopy did not reach its full height until June of the following year. The reduced shading from shorter vegetation probably provided better conditions for the young plants, which in turn led to higher survivorship and increased abundance. In western Oregon, annual spring to early summer mowing timed to coincide with peak flowering and above-ground allocation for a non-native grass, *Arrhenatherum elatius*, led to a significant reduction in flowering and cover after 2-3 years of treatment (Wilson and Clark 2001). In addition, after 3-4 years, the native grasses *Festuca roemeri* and *Danthonia californica* increased significantly, as well as some non-native grasses. However, native forbs did not increase. The authors suggests that treatment effects may take time to manifest themselves, especially for the native grass community, and that timing is critical to get the best results.

Mowing may be beneficial at increasing forb diversity and reducing non-native annual grasses. In a coastal California grassland, dominated by two non-native annual grasses (*Lolium multiflorum* and *Bromus diandrus*), mowing and biomass removal led to a substantial increase in species richness compared to the control. This increase in diversity was primarily due to a doubling of the number of forbs species, both native and non-native (Maron and Jefferies 2001). It was hypothesized that the reduced litter helped improve the germination and establishment environment. In contrast, mowing and biomass removal resulted in a large decrease in the non-native grasses, primarily due to the removal of seed, but possibly also litter. In the Midwest, Weber (1999) and Kurtz (2001) recommend after a fall planting, mowing at a height of three to six inches (depending on rainfall, soils and weed height) two to three, or more times during the first season starting in June, and maybe at least once the next season. In Iowa, workers found that an area left unmowed had only eight species compared to 27 species in a mowed area (Kurtz 2001).

Grazing Grazing can sometimes be more beneficial than mowing, because grazers can create more micro-sites and openings for seedling recruitment (Sykora et al. 1990), and promote more heterogeneity due to their preference for certain plants (van den Bos and Bakker 1990). In the United Kingdom, when researchers seeded five native forbs (*Achillea millefolium, Plantago lanceolata*, *Centaurea nigra*, *Stachys officinalis*, *Prunella vulgaris*) into a dense stand of grasses (*Lolium perenne*, *Poa* spp. and *Agrostis* spp.), it was found that plots mowed once or twice in the summer and grazed from October through January (with sheep) had higher establishment rates than plots that were mowed but not grazed (Jones and Hayes 1999). The authors suggest that grazing in the fall/winter created openings in the sward and improved light conditions for germination, and mowing in the summer reduced competition and shading of seedlings. Intensive, short-duration grazing in California helped to control non-native annual grasses following seeding of native perennial bunchgrasses (Stromberg and Kephart 1996). However, other researchers have reported that grazing can have negative effects on perennial grass seedlings (Salihi and Norton 1987, Dyer et al. 1996). Salihi and Norton (1987) found that grazing when plants are still seedlings can lead to high mortality due to trampling.

Adding additional seed It may be necessary to re-seed or add more species diversity to a prairie after the initial sowing (Wilson 2002). In circumstances where unusually dry conditions coincide with sowing native seeds, many seedlings may die due to lack of sufficient moisture (Dyer et al. 1996). In these situations some native plant species may fail to establish and will need to be sowed again. When Bakker et al. (2003) sowed seeds of native grasses during each of three consecutive years in semiarid Saskatchewan, they found that establishment and survivorship rates varied four-fold and up to eight-fold respectively, over the three years. This variation was significantly correlated with June and July precipitation. The authors suggest that practitioners “may require opportunistic exploitation of wet years for seedling establishment”.

Long-term management

Most of North America’s prairies evolved and were maintained by climatic conditions and regular disturbance regimes (Holland and Keil 1995, Crawford and Hall 1997, Packard and Mutel 1997). To restore and maintain ecological processes and functions of prairies over the long term we must simulate many of these past disturbances. Burning, grazing, and mowing, and combinations of these are the most likely tools for use in long-term prairie management. Fire can have an affect on species diversity, non-native abundance (Howe 1994 and 1995, Tveten and Fonda 1999, Copeland et al. 2002), litter, nutrient levels, and native species establishment. Burning of newly established prairies is generally not recommended until after the third year because there is usually not enough fuel to carry a fire (Pauly 1997, Kurtz 2001).

Burning

Burning in the Midwest and West Coast prairies   Most burns in the Midwest now occur in the fall, winter and spring dormant seasons whereas prior to European settlement fires were ignited by lightening storms during the growing season when conditions were dry (Mlot 1990, Howe 1994) and by Native Americans in the fall (Anderson 1997). Non-growing season fires tend to favor large C_4 warm-season grasses and forbs and lead to lower species diversity, whereas growing season fires suppress dominant warm season grasses and forbs which results in a competitive release of subdominants the following season and an increase in species diversity (Howe 1995, Copeland et al. 2002). Howe (1994) recommends that burn season and burn interval be varied over time to promote greater species diversity and better mimic the varied conditions under which prairies evolved.

Most burns on the West Coast are done in the fall dormant season after native plants have produced seed. It would be desirable to burn in the spring to control the cool season European grasses that have become established in West Coast prairies, but doing so would damage the dominant native cool season species as well. It may be possible to take advantage of phenological differences between native and non-natives on the West Coast and time the burns to have maximum negative impact on the undesirable species. Further research is needed to explore whether this is possible and practical. The situation is different in the Midwest. Spring burns could be used to reduce the non-native cool season grasses in areas where native warm season grasses dominate. Most of the results from burn research described below are relatively short term studies, between two to five years.

Fire effects on non-native species Fire can be used to reduce the abundance of woody species that invade prairies (Pendergrass 1995, Pauly 1997, Wilson and Clark 1997, Clark and Wilson 2001), however burning may only top-kill young saplings, which often re-sprout. Repeated burns or other measures such as cutting, mowing or herbicides may also be necessary for long-term control (Pendergrass 1995). In a western Oregon wet prairie, twice burned (sequential years) treatments resulted in a 64 percent decline in tree density compared to only a 13 percent decline for a single burn (Pendergrass 1995). In this same study, shrub density (mainly rose spp.) increased by as much as 53 percent while shrub height declined. There was also an increase in tree and shrub seedlings in all burn treatments. In another Oregon wet prairie, Clark and Wilson (2001) found that after two burns, one in 1994 and another in 1996, about 67 percent of woody vegetation was killed compared to only about 17 percent in the control. Although mowing was found to be ineffective at controlling woody vegetation in this study, another study by Wilson and Clark (1997) in a nearby upland prairie found that mowing for three consecutive years resulted in about a 66 percent reduction in woody vegetation cover compared to the control. Since mortality was not measured in this study, many of the plants were probably still living and capable of sending up new shoots. In Western Washington, fires on a 3-5 year rotation effectively reduced cover of a non-native shrub (*Cytisus scoparius*) and killed invasive conifer trees which helped to maintain the open prairie habitat (Tveten and Fonda 1999).

Fire effects on non-native herbaceous plants are mixed (Parsons and Stohlgren 1989, Pendergrass 1995, Taylor 1999, Jancaitis 2001, Wilson et al. 2004). In an Oregon wet prairie, research showed that burning did not significantly reduce herbaceous non-native plants (Wilson et al. 2004). The average percent cover of pest species after the first year in burn plots was 40 percent compared to 33 percent for the control plots. In another study nearby in an upland prairie, Maret and Wilson (2000) found that burning significantly increased seedling establishment of some non-native species compared to unburned plots, including *Centaurea cyanus, Daucus carota*, *Hypochaeris radicata,* and *Taeniatherum caput-medusae*. A long term study in an Oregon wet prairie, Taylor (1999) verified these mixed findings by showing that some natives (e.g.,*Camassia quamash*) and some non-natives (e.g., *Hypochaeris radicata*) which showed an initial increase in population after burning, retained this advantage 10 years after burning ceased. Pendergrass (1995) also showed varied species specific responses in a study of vegetation after one, two, or three consecutive annual burns, whereby many species (both native and non-native) increased, many decreased, while others showed little effect. In a western Oregon upland prairie, burning led to a 5 percent decrease in non-native forb cover compared to an increase of 2 percent for the control plots; in contrast, non-native grass cover was not significantly affected by burning (B. Johnson, pers. comm. 2004). Annual burning at a military installation in western Washington (ignited by artillery) drastically changed a native perennial bunchgrass prairie to one dominated by non-native forbs and annual grasses (Tveten and Fonda 1999). In the Sequoia National Park grassland area in California, Parsons and Stohlgren (1989) found that repeated burning in the fall and spring led to some decrease in biomass in non-native annual grasses, however there was a very large increase in the non-native forbs (up to 18,000 percent increase). The authors found that fall burns promoted non-native forbs more than native species whereas spring burns promoted both about equally. In a wet prairie in Oregon, Jancaitis (2001) found, of 10 non-native species studied, three increased in frequency and two decreased after burning.

Fire effects on native species   Fire effects on native seedling establishment, plant diversity, flowering, and biomass can be variable (Pendergrass 1995, Wilson and Clark 1997, Pendergrass 1999, Clark et al. 2001, Jancaitis 2001, Seabloom et al. 2003a). In a western Oregon wet prairie where native seeds were sown one year after burning, there was no difference in overall seedling establishment in plots that were burned (7. 0 percent) compared to those that were unburned (8.7 percent) (Clark et al. 2001). However, for the seven native species that did respond positively to burning, there was a two-fold increase compared to no burning. The overall response to burning may have been higher in this study if the seeds had been sowed soon after burning to take advantage of the bare ground, reduced litter, and leachate from charred remains of the fire. In many fire-prone communities, seeds of certain species may be cued to germinate after experiencing a fire (Keeley and Fotheringham 1998). Studies have found that smoke or leachate from charred remains may promote an increase in seed germination, faster rate of germination, and more rapid seedling growth (possibly due to increased root growth) (Brown and Van Staden 1997, Keeley and Fotheringham 1997, Blank and Young 1998). Since most research in this area has focused on chaparral species, additional research is needed to understand how smoke and leachate might effect prairie seed germination behavior.

Seabloom et al. (2003a) found that burning had no effect on the abundance or richness of native species without seed addition. Wilson and Clark (1997) in western Oregon found that two native lupine species had twice the number of inflorescences after burning than in the control. In contrast, a nearby study found that a native wetland prairie grass (*Deschampsia cespitosa*) had approximately 50 percent less aboveground vegetative biomass and approximately 85 percent fewer reproductive units after burning compared to unburned plots (Clark and Wilson 1998). Jancaitis (2001) found, of 18 natives studied, seven forbs and one graminoid increased in frequency, and one native graminoid decreased. The native that decreased was Danthonia californica, a dominant wet prairie grass. Its decrease likely opened up space for other forbs. In an upland prairie in western Oregon, burning led to a 9 percent increase in native forb cover compared to a 5 percent decrease in control plots (B. Johnson, pers. comm. 2004).

Fire can reduce litter and vegetative height, which can influence light and temperatures near the soil surface. Without fire, litter accumulation can occur to the point where it may limit aboveground productivity due to reduced light and space (Boerner 1992) and reduce survival rate of seedlings (Fowler 1988, Bosy and Reader 1995). Fowler (1988) hypothesizes that seedling mortality may be higher under deep litter because seedlings might germinate in the litter above the soil, experience excessive shading or succumb to pathogens that reside in litter. In a western Oregon upland prairie, pathogen damage to native species was reduced after burning compared to the control, unlike non-natives, where there was no difference (B. Roy, Pers. comm. 2004). This reduction in pathogens may increase plant reproductive fitness. Litter may also suppress seedling emergence by forming a mechanical barrier and leaching chemicals that may be inhibitory (Bosy and Reader 1995). The authors also found that overall, small seeded forbs were more affected by litter than large seeded forbs, such that emergence rates for large seeds were reduced by 25 percent to 41 percent compared to 100 percent for small seeds.

Increased growth after a fire may be more related to increased light, space, and temperature than to nutrients mineralized by fire (Hulbert 1988). Fire can also start the growing season earlier and thus increase the rate of phenological development (Hadley and Kieckhefer 1963, Knapp and Seastedt 1986, Pauly 1997). Phenological development can be accelerated by as much as four weeks because leaf litter and vegetative top growth is reduced, which allows the bare soil to be warmed by the sun's radiation. This warmer soil contributes to increased root growth, tillering and shoot densities earlier in the season (Knapp and Seastedt 1986). Furthermore, shading in undisturbed prairies can lead to a four week delay in shoot emergence, and photosynthetically active radiation (PAR) intercepting the shoots can be reduced by 58 percent compared to sites without litter.

In an Illinois prairie dominated by either big bluestem (*Andropogon furcatus*) or Indian grass (*Sorghastrum nutans*), both warm season grasses, Hadley and Kieckhefer (1963) found that living shoot and root biomass and flowering stalk production of both native grasses significantly increased with spring season fire frequency. Big bluestem flower production in burned plots increased greater than 10 fold while root biomass increased about 37 percent compared to unburned plots (burning took place in 1952, 1959, and 1961). In plots where burning was excluded for one year, shoot biomass and flowering stalk production showed a greater than 50 percent decline. Phenological development happened sooner in burned areas, where flowering occurred 7 to 10 days earlier than in unburned areas. It was suggested that the reduction of litter by the fire probably produced the changes. Litter was reduced by 65 percent compared to the control.

Certain plant nutrients may increase after burning (Boerner 1982, Pauly 1997). Although some nutrients such as potassium and phosphorus may increase after a fire (Brockway et al. 2002), most nitrogen is volatized by fire and lost to the atmosphere (Boerner 1982, Brockway et al. 2002). Most of the increase in nitrogen is due to indirect stimulation of microbial activity (nitrification) in the soil by warmer temperatures. Additional nitrogen can come from legumes (capable of symbiotic nitrogen fixation) which tend to increase in abundance after a fire (Boerner 1982).

Timing and frequency of fires can influence plant biomass and plant diversity. Tveten and Fonda (1999) found that burning on a 3-5 year rotation in the fall was better than annual burns or spring burns at maintaining the native forb and grass community. They also found that prescribed burns initially reduced cover and biomass of graminoid species such as Roemer's fescue (*Festuca idanoensis* var. *roemeri*) but no plants were killed and they continued to maintain dominance. In Kansas at the Konza prairie research site, annual spring burning resulted in low species diversity, mainly due to an increase in the dominance of C_4 grasses and reduced forb abundance (Collins et al. 1998). When grazing by bison was added to the burning treatment, then C_3 forbs and grasses increased in abundance, suggesting that a combination of burning and grazing may be better than burning alone in promoting species diversity. In a western Oregon wet prairie study (unreplicated and no native seed added), annual burning resulted in improved prairie conditions (meaning an increase in natives and decrease in non-natives and woody vegetation) compared to triennial burning and the control (Wilson 1999). Copeland et al. (2002) found that late summer growing season fires in Illinois resulted in a doubling of the mean frequency and richness of subdominant species, whereas early season fires had no effect on subdominant species. Furthermore, they found no change in the presences of non-native or uncommon prairie species, for both early and late season fires. It seems that the vigor of the warm season grasses was not reduced. Flowering for the warm season grass, big bluestem (*Andropogon gerardii*) increased 11-fold (in the following season) for the late summer fire. Interestingly, tillers of the dominant warm-season grasses were not significantly reduced. Howe (1995) had similar findings regarding summer and spring fires. He found that in a restored prairie in Wisconsin with two burn cycles (spring and midsummer) at three year intervals warm season grasses and forbs accounted for 97 percent of the cover in spring burns compared to 66 percent cover for midsummer burns. This reduction in warm season grasses and forbs in areas with midsummer burns allowed seedling recruitment of earlier flowering species and an increase in species diversity.

Grazing and mowing

Historically, bison were the main grazers in the Midwest prairies, while elk, pronghorn antelope and deer grazed in West Coast prairies (Holland and Keil 1995, Steuter 1997). Starting in the 1700s and 1800s, ranchers began to replace native herbivores with cattle, horses and sheep, which often led to heavy overgrazing, especially in California (Schoenherr 1992, Kimball and Schiffman 2003). Grazing, as a method to enhance or restore grasslands, has produced mixed results depending on grazers used (Steuter 1997), soil types (Harrison et al. 2003), frequency and timing (Salihi and

Norton 1987, Biondini and Manske 1996, Jackson 1999), and types of plants (Hobbs and Huenneke 1992, Hatch et al. 1999, Kimball Schiffman 2003).

Grazing and mowing can be important management tools in prairie systems for reducing trees and shrubs, thereby interrupting succession to woodlands (Hobbs and Huenneke 1992). In a western Oregon upland prairie, annual mowing for three years reduced woody vegetation cover to 40 percent of unmanipulated plots compared to a 50 percent change for plots that were burned twice in three years (Wilson and Clark 1997). In contrast, in a western Oregon wet prairie, when mowing occurred biennially there was no significant difference in woody vegetation cover between mowing and the control (Clark and Wilson 2001). It difficult to say why mowing was more effective against woody vegetation in the upland compared to the wet prairie. It could be that wet prairie woody vegetation is more resistant to cutting because of higher moisture reserves. Since many woody species resprout after mowing and fire, long-term reduction will require repeated treatments. Wilson and Clark (1997) suggest combining burning and mowing as an alternative approach.

Under the right conditions and appropriate stocking rates, bison can promote species diversity by reducing grass dominance, mainly because of their preference for grasses over forbs (Steuter 1997, Collins et al. 1998). A bison's diet typically consists of 90 percent to 95 percent grasses and sedges. Bison can also promote species diversity by creating disturbance through their wallowing and trampling. If a restoration site has cool season non-native grasses, bison can reduce their dominance if they are grazed in the fall, winter and spring, because they selectively graze younger growth (Steuter 1997).

Jackson (1999) suggests that continuous grazing with cattle in tallgrass prairies probably leads to a loss of native species. He advocates rotational grazing, after natives are established, as a potential tool to help restore prairies in the Midwest. In a California valley study, where vegetation was clipped (to simulate grazing) at different frequencies in the spring (late February through early April), there was a significant reduction in cover and species richness of natives (Kimball and Schiffman 2003). In contrast, non-native cover and species richness was unaffected or decreased slightly, but only after grasses were clipped two or three times. In a central coastal California grassland study, continuous grazing by cattle led to about a 10 percent increase in cover for the native bunchgrass, *Danthonia californica*, compared with an average decline of 12 percent in ungrazed plots (Hatch et al. 1999). Two other native grasses in the same study, *Nassella lepida* and *Nassella pulchra*, showed mixed effects from grazing. Cover of *N. lepida* declined an average of 5 percent in all plots, whereas *N. pulchra* did not show any significant change (Hatch et al. 1999). The results from this study indicate that management that favors one native species may be detrimental to another. The authors suggest that "conflicting responses to management" may be quite common and will therefore require a more comprehensive and adaptive management strategy to be successful.

Table 1. A description of the various steps, objectives, and techniques used to restore prairies.

Step	Description of objectives	Restoration Techniques
1	Kill existing non-native vegetation	• Cultivation techniques (tilling, disking, plowing, harrowing) • Herbicides
2	Control the non-native seed bank	• Repeated shallow tilling • Herbicides • Infrared burners and flamers • Solarization
3	Improve the competitive environment for natives	• Carbon addition/nutrient immobilization • Mycorrhizal inoculation
4	Successful planting of native species	• Drilling and broadcasting • Using different seed mixes • Planting propagule types (e.g., bulbs, plugs)
5	Successful post-seeding management	• Hand weeding • Herbicides • Mowing • Grazing • Adding additional seed • Prescribed fire • Grazing

Table 2. A summary of the advantages and disadvantages of restoration techniques. Note asterisk indicates techniques best suited for relatively small restoration projects.

Restoration phase	Restoration technique	Advantages / benefits	Disadvantages / concerns
Site preparation	Cultivation	• Can kill existing non-native vegetation • Prepares a seedbed • If shallow tilling is repeated, it may help exhaust the non-native seed bank	• Can bring buried seed to the surface to germinate • Usually needs to be repeated over several years • Can lead to erosion • Damages natural microtopography and reduces below-ground flora and fauna such as mycorrhizae
	Herbicides	• Can kill existing non-native vegetation • Can target non-native broadleaf and grasses separately • Herbicides applied with a wick can target taller non-native species while leaving lower growing species undamaged • Results in minimal soil disturbance • Is usually less expensive than other techniques	• Provides only short term control of weeds unless repeated • Drift can kill desirable species • Some weeds are becoming resistant to glyphosate • Repeated applications of some herbicides can lead to ground-water contamination • May have lethal or sublethal toxic impacts on below ground microflora and fauna, non-target plants, and wildlife
	*Flamers/Infrared burners	• Can kill weed seedlings, many annuals, surface weed seeds, and possibly superficially buried seeds, depending on the temperature of the flames • Results in minimal soil disturbance • Can be used in place of broadcast burning when fuels are insufficient or too green	• Commercial flamers may not readily available • Fuel costs can be expensive • Only top kills most perennials • Can be a fire hazard during dry conditions • Application rate is relatively slow
	*Solarization	• Can kill emerging seedlings, surface weed seeds, and some existing vegetation and seeds superficially buried (if the soil is sufficiently moist and high enough temperatures are reached)	• Requires labor intensive methods or specialized equipment to cover the soil with large sheets of plastic, which may be expensive • Requires several months of sunny weather • Damage, weather, or improper installation can reduce effectiveness. • Plastic sheeting may need to be sent to a landfill
	Combining techniques	• Can target different life stages of plants, including seeds, seedlings, and adults • Can be more effective than most single treatments	• Will entail more coordination, time, and costs than single treatments • May require using specialized machinery
Improving the competitive environment for natives	*Carbon addition	• Depending on the level of carbon addition, it can reduce nitrates, thereby impacting weeds, and promoting natives.	• May require tilling and incorporating carbon into the soil • The carbon source could be expensive depending on the type used • May not be practical if nitrate levels are too high • May not be effective against established perennials
	Mycorrhizae	• Mycorrhizae can benefit natives through increased seedling survival, emergence, growth, and survivorship	• It may be difficult, time consuming, and expensive to propagate a diverse and locally adapted mycorrhizae community

* These techniques are best suited for projects 50-100 acres, depending on the type of machinery used and the cost and availability of labor.

Table continued.

Restoration phase	Restoration technique	Advantages / benefits	Disadvantages / concerns
Seeding and planting	Drilling	• Fewer seeds are needed and it may lead to higher emergence rate, especially under dry conditions, compared to broadcasting • A no-till drill does not require cultivation • Good in areas with high sheet flows—burying seed keeps it from washing away	• Some seeds that require light may not germinate • Is less aesthetically pleasing due to the "row effect" • May lead to lower survivorship due to competition
	Broadcasting	• May lead to higher survivorship compared to drilling • Is more aesthetically appealing because there is no "row effect" • Seeds that require light are more likely to germinate	• May require up to twice the amount of seed • Seed may dry out which could lead to a low emergence rate
	*Planting	• For species that do not establish well from seed, planting bulbs, plugs, or bare-root stock may be more effective • Raising plugs from seed is an efficient use of limited seed • Planting forb plugs into established grasses can lead to higher establishment rates than if seeded	• Will be more expensive than sowing seeds • May require a greenhouse • May need supplemental watering the first summer to ensure survival
Post-seeding management	*Hand weeding	• Can be effective, especially when herbicides are not an option and there is a need for selective weeding • Less chance of collateral damage compared to herbicides (although trampling may be a problem) • Will create some soil disturbance	• Will likely be more expensive than herbicides • Requires a low-priced but trained labor pool
	Herbicides	• Spot spraying and wick application of herbicides can be cost efficient and effective • Results in minimal soil disturbance	• May lead to collateral damage • For other disadvantages see Herbicides under Site Preparation
	Mowing	• Reduces weed seed production and increases light for slow growing natives • Can suppress dominant species and lead to higher species diversity, especially for forbs • Can reduce woody vegetation if done over multiple years	• May require two to three mowings during the first year • May create some disturbance
	Grazing	• Can substitute for mowing • Can promote more heterogeneity than mowing due to preference by grazers • Can reduce woody vegetation if rotational grazing is used	• Trampling may kill young seedlings • Requires fencing and more management than mowing • Continuous grazing (overgrazing) can lead to loss of native species and an increase in non-natives
	Burning	• Can reduce woody vegetation if burns are repeated • Can kill surface non-native seeds and some non-native vegetation • Can reduce litter which can lead to accelerated phenological development and increased seedling survival and growth • May stimulate increased growth and flowering in some species • May lead to an increase in certain nutrients such as potassium and phosphorus • May reduce pathogen damage to natives which may increase plant reproductive fitness	• Requires specialized training to conduct a burn • Annual burning may lead to an increase in annuals (both native and non-native) • May lead to an increase in non-native abundance • May reduce abundance, growth, and flowering in some natives

* These techniques are best suited for projects 50-100 acres, depending on the type of machinery used and the cost and availability of labor.

CONCLUDING REMARKS

One of the essential lessons learned by restoration ecologists and practitioners trying to restore native prairie, is that there is not one technique or combination of techniques that works for all restoration sites, i.e., there is no magic bullet. Restoration techniques will need to be site specific and may depend on many things including past disturbance events, assemblage of plants including non-natives and natives, and site conditions such as soils, topography, hydrology, fauna, climate, etc.

I discussed a number of restoration techniques that can reduce non-native species and improve the ecological function of prairies, some of which include tilling, herbicides, thermal weed control, mowing, carbon addition, grazing and burning. Perhaps the three most important things to consider when doing a prairie restoration include: 1) Using a combination of techniques that target different life stages of plants (seeds, seedlings, adults) and then do these treatments multiple times over several seasons. 2) Allowing for enough time to reduce the weed seed bank and non-native vegetation before sowing in native seed. 3) Incorporating post-seeding management of non-natives in the first two years after seeding in natives. Many restoration projects do not take the necessary time to reduce the weed seed bank and non-native vegetation and consequently end up with non-natives overwhelming and outcompeting natives, with very little hope of success. Some researchers suggest sampling or monitoring the seedbank prior to and after site preparation in order to gain insights into what non-natives may be problematic and to evaluate which treatments are most successful at reducing the seedbank (D'Antonio and Meyerson 2002, Wilson et al. 2004). In an Oregon wet prairie, as many as 20,000 seeds per m^2 were found in control plots, with nearly 40 percent being non-native (Wilson et al. 2004). The authors suggest that at least two years will be needed to reduce the weed seedbank and non-native cover at this site. To be successful, Wilson et al. (2004) proposes monitoring both the non-native cover and the seedbank during the site preparation phase, and they suggest reducing non-native cover to < 30 percent and viable non-native seeds to < 2000 seed per m^2. Monitoring at all phases of the restoration process provides critical information so adaptive management can be used to improve results and it allows one to evaluate when success has been achieved.

In the future we may have more techniques available to reduce weeds and the seed bank, including: equipment that sprays hot water (Hansson and Ascard 2002); mobile steaming equipment, that has potential to kill most weed seeds in the top 10 cm of the soil (White et al. 2000, Bond and Grundy 2001); and equipment that can pass soil, recently cultivated and set in ridges, through a chamber heated to 68-70° C (William 1999). Other methods that could potentially kill weeds include electroporation, where electric pulses are applied to the soil, CO_2 lasers, ultraviolet light, and microwaves (Bond and Grundy 2001, Barberi 2002). Another method that uses activated carbon to protect plant plugs or emerging seedlings from pre-emergent herbicides (Lee 1973, Steinegger et al. 1987) may have potential in prairie restorations. The method consists spreading approximately a 2-5cm width band of carbon slurry over newly sown seed and then spraying a pre-emergent herbicide (e.g., diuron) for controlling non-natives. The purpose of the activated carbon is to detoxify herbicides in close proximity to emerging seedlings. A number of studies have found that using activated carbon protected young seedling, led to a reduction in non-natives and a positive response in yields for crops such as lettuce, watermelon and commercial grasses (Lee 1973, Kratky 1975, Glaze et al. 1979). A trial is presently being done in an upland western Oregon prairie to see if this method is effective at reducing competition between native grass seedlings and non-natives (D. Clark, pers. comm. 2004).

Some of these methods or equipment mentioned above are at the evaluation or experimental stages while others are commercially available and being tested. It may be years in the future before some of these methods become practical, while others may prove too expensive for field use.

There is a need for more research to determine the optimal fire frequency and intensity, and combination of techniques that will effectively reduce non-native vegetation and the seed bank and promote natives for different site conditions and regions of the country. There is also a need to look at ecological responses to various restoration techniques. A study presently underway in Oregon will hopefully provide some answers to these questions. This study will investigate plant and soil responses to various prairie restoration treatment combinations using scientifically rigorous methodology. The wetland site has been used for grass seed production since the 1970s and has been in annual ryegrass (*Lolium temulentum*) production for approximately the past ten years. Researchers will test the effects of various treatment combinations, including solarization, tilling, herbicide, infrared burning, and nutrient immobilization using carbon addition, on controlling non-native species and enhancing native species establishment. Scientists will also look at how these treatments influence plant community structure, diversity, and plant productivity both above and below the surface. In addition, measurements of the seed bank, functional soil ecosystem attributes, and physical and chemical properties of the soil will be taken to help understand how the restoration techniques affect various ecological attributes. Results from this study should provide insights on how multiple treatments can influence the success of prairie restoration.

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