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Fire As a Tool For Controlling Nonnative Invasive Plants

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CENTER FOR INVASIVE PLANT MANAGEMENT

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INTRODUCTION

This review focuses on the intentional use of fire, alone or integrated with other methods, to control exotic plants in North America. The literature search was intended to retrieve all published articles and abstracts where fire was used to suppress exotic plants. Approximately 235 citations were available as of January 2004. The initial section on Managers' Objectives includes summary statements primarily from articles that do not include supporting data. The Detailed Case Studies section, organized by life form, relies primarily on publications that have data on target plant response but occasionally include unsubstantiated management suggestions.

Precise knowledge of invasive plant morphology, phenology, and life history is required to select a suppressive burn prescription (Pyke et al. 2003). Life history determines the direct susceptibility of weeds to fire. Optimizing longer-term control would include consideration of a burning regime that promotes desirable plants as well as injuring the target weeds. The potential to utilize prescribed burning for weed control varies by environment and habitat type. Fuel quality and quantity, fire behavior, and competing vegetation will influence the target weed response.

PREVIOUS REVIEWS

A number of partial reviews of fire and invasive plants have been published. The most comprehensive has been by the Tall Timbers Research Station (Galley and Wilson 2001), especially the chapters on deserts (Brooks and Pyke 2001), temperate grasslands (Grace et al. 2001), California Mediterranean climate ecosystems (Keeley 2001), and coniferous forests (Harrod and Reichard 2001). A review of case studies testing experimental burning for weed control in varied habitats in North America and Australia summarizes five successful examples and 14 that failed (D'Antonio 2000). Two Australian reviews (Downey 1999; Johnson and Purdie 1981) are of interest as they include exotic weeds that are also problematic in North America. A short review of Japanese honeysuckle management has fire control citations (Evans 1982). A short manager-oriented summary of options to use fire to control herbaceous and woody exotics in the Midwest is based mostly on citations to the Illinois Nature Preserve Commission (Grese 1992). A review of 25 publications on the use of prescribed fire to control 8 species of exotic grasses common in Iowa tabulated 55 cases (53% of all cases) for which there was no change or an increase in exotic grass abundance and 48 cases (47% of total cases) for which the exotic grass abundance decreased (Rosburg 2001). An Integrated Pest Management review focused mostly on arable lands and some pasture-grassland settings includes thermal weeding as well as prescription burning (Hatcher and Melander 2003). There is a 1964 literature review pertaining to the opportunity for controlling downy brome (*Bromus tectorum*) by burning (Klemmedson and Smith 1964). The monograph by Wright and Bailey (1980) on Great Plains fire ecology includes a review of early work using prescribed burning to suppress exotics, primarily cool-season grasses in mixed and tallgrass prairie. Prescribed burning tactics, or the ineffectiveness of burning, are included in a restoration handbook for prairies and savannas (Solecki 1997). The handbook does not include supporting data. A second managers' handbook provides examples of weeds controlled by burning based primarily on manager observations (Tu et al. 2001).

MANAGERS' OBJECTIVES

Prevent Flowering or Seed Set

Burning yellow starthistle at the early flowering stage can provide control (Thomsen et al. 1991). Cured annual grasses provide the fuel. Prescribed burning of second-year biennial sweet clover (*Melilotus* spp.) species is employed to prevent formation of a new seed crop (Kline 1983; Kline 1984).

Destroy Seeds

Seeds may be tolerant of certain temperatures and duration of heating or they may avoid heat by dropping to the ground.

In inflorescences

Greenhouse trials showed reduced germination of spotted knapweed (*Centaurea biebersteinii*) seeds heated in muffle furnaces at temperatures and durations obtainable in some grassland burns (Abella and MacDonald 2000). Data indicate that germination was significantly reduced for seeds heated to 392°F (200°C) for 120 and 240 seconds, or to 752°F (400°C) for as short as 30 seconds. The authors suggest that some reduction in germination could begin at temperatures somewhere above 212°F (100°C) and durations greater than 30 seconds. They state that spotted knapweed retains seed in the inflorescence until the early fall and suggest that it should be possible to control spotted knapweed if there is enough fine fuel to sustain an intense fire. However, Renney and Hughes (1969) state that burning is not a suitable tool for killing spotted knapweed seeds because the seeds are normally shed soon after they ripen. Renney and Hughes (1969) suggested that diffuse knapweed (*Centaurea diffusa*) seeds were possibly susceptible to prescribed fire because they are held in the flowerhead.

Burning the seeds of annual grasses before they shatter is a goal of many restoration managers (Allen 1995; Kan and Pollak 2000; Menke 1992). Burn temperatures are higher in a fine fuel canopy than at the soil surface. If the burn can be done before the seed is fully cured, the higher water content increases the embryo susceptibility to heating (Brooks 2001). Backing fires will increase the duration of heating of the seeds. Deferring grazing will allow more fuel for the burn (George 1992) and reduce seed shatter if the burn is made after seed maturation (Major et al. 1960). Major et al. (1960) provide a concise summary of using these timing and fuel factors for the suppression of medusahead (*Taeniatherum caput-medusae*).

In litter layer and at soil surface

Grassland fires seldom damage seeds on or near the soil surface (Daubenmire 1968a). A May burn was applied to remove annual grasses from a severely degraded coastal sage scrub site in California (Cione et al. 2002). Then various treatments (nitrogen, mulch, grass removal, or herbicides) were applied to facilitate reestablishment of seeded native species. The May burn was after seed dispersal by the exotic annual grasses. The investigators noted that there were many seeds of these exotic annual grasses lying on the soil surface after the controlled burn.

The seeds of downy brome begin to shatter shortly after the culms cure to the degree that they would carry a fire. Consequentially, for most of the year almost all the seeds are in the litter or on the surface of the soil, so considerable woody fuels are needed to destroy these seeds (Evans and Young 1987; Young and Evans 1978). Herbaceous fuels alone do not burn long enough to destroy downy brome seeds after they have shattered to the ground, but woody fuels can extend the duration of heating long enough to destroy seeds at the surface.

In soil

Post-fire soil nutrient conditions in California maritime chaparral allowed exotic Hottentot-fig (*Carpobrotus edulis*) to have faster growth and establish well (D'Antonio et al. 1993). The investigators suggest that prescriptions for burns in California chaparral that maximize soil temperatures (>212°F or 100°C) would cause mortality of the Hottentot-fig seeds while stimulating germination of native chaparral species. They also suggest that small burns would increase brush rabbit grazing of Hottentot-fig seedlings because the brush rabbits do not forage far from shrub cover.

Stimulate Simultaneous Germination

Broom (*Genista, Cytisus*) stands are burned to stimulate germination from the persistent seedbank. Often the topgrowth is cut and allowed to dry first so the fire will carry. The heat of the burn scarifies the broom seeds and thus promotes subsequent germination. It takes two or three years before the new plants will set seed. A follow-up treatment with herbicides or fire is implemented before new seeds are produced. The repetition of prescribed burns before reproductive age is likely to result in a much higher fire frequency than the historic regime and thus may have an adverse impact on some native plants. It has been suggested, but not tested, that first burning exotic Lehmann lovegrass (*Eragrostis lehmanniana*) stands to stimulate seedbank-depleting germination, then a follow-up herbicide treatment to kill juvenile and surviving adult Lehmann lovegrass plants prior to seeding the desired natives would be a potential control strategy (Biedenbender et al. 1995). Burning is suggested to stimulate kudzu seeds so it can be controlled by follow-up treatments (Everest et al. 1991). Burning medusahead litter would bring seed into contact with the soil where it would germinate and could be subsequently destroyed (Torell et al. 1961).

Deplete Carbohydrate Reserves

Repeated slash-and-burn and standing-burn fire treatments are used to suppress the amount of resprouting from woody species like saltcedar (*Tamarix* spp.) (Burke 1990). In eastern and mid-Atlantic ecosystems, most prescribed burning is done during the dormant season, but some foresters suggest that growing-season burns would be more effective in long-term suppression of woody exotics (Richburg et al. 2001; Richburg and Patterson 2003b). Dormant-season burns are usually followed by profuse resprouting from the rootstocks of many woody exotics. However, total nonstructural carbohydrate reserves are lowest during the growing season, and burning late in the growing season may not allow enough regrowth time to replenish depleted root carbohydrates. Cutting in early summer then burning late in the summer prevented full recovery of nonstructural carbohydrates for at least two years in some woody exotics (Richburg and Patterson 2003a). Grace (1998, 2001) has also suggested that growing-season burns are more effective than dormant-season burns in suppressing resprouts in his studies of Chinese tallow (*Sapium sebiferum*).

Kill Perennating Tissue

It is generally not feasible to fire-kill perennating tissues because they are usually belowground. However, Steuter (1988) used repeat burning to effectively suppress absinth wormwood (*Artemisia absinthium*) for which the perennating buds are at or near the soil surface.

Site Preparation Burns

Facilitate planting or establishment

Prescribed burning of annual exotic grasses may reduce competition long enough to allow establishment of desirable species by planting (Goodrich and Rooks 1999). If establishment is successful, the desirable plants may help resist increasing abundance of undesirable exotics. This IPM strategy is often constrained as a restoration method because of a lack of appropriate native plant materials.

Fall burning was used to prepare the seedbed of three grassland communities in the foothills of coastal Oregon (Maret and Wilson 2000). The late-September burns were applied to small plots in sites dominated by exotic annual grasses, an exotic perennial grass, tall oat grass (*Arrhenantherum elatius*), or native bunchgrasses. Seeds of exotic grasses, exotic forbs, native grasses, and native forbs present in the area were then sown into the burned and no-burn control plots two weeks after the burns. Seedling emergence and survival were followed through the next spring. The burning promoted exotics in the native bunchgrass site, but native grasses and forbs improved on the sites that were dominated by the annual and perennial exotic grasses.

Spring burning of abundant litter was done to facilitate drill-seeding of tallgrass prairie grasses in combination with herbicide treatments of leafy spurge and other exotic plant infestations (Masters and Nissen 1998; Masters et al. 1996).

Increase herbicide efficacy

Winter or early-spring burning is suggested as a pretreatment for herbicide suppression of Japanese honeysuckle (*Lonicera japonica*) and kudzu (*Pueraria montana* var. *lobata*) (Brender 1961; Everest and others 1991; Missouri Department of Conservation 2003; Moorhead and Johnson 2002; Shipman 1962). Some seedling and seed mortality may occur from the burn, but the goal is to remove canopy and litter so herbicides can easily contact leaves resprouting from the underground perennating tissues. Brender (1961) also suggested that winter burning of the litter layer could expose kudzu rhizomes to freezing injury.

Prescribed fire is used in dense saltcedar (*Tamarix* spp.) stands to remove the biomass and provide access for secondary herbicide application (Egan 1999; Friederici 1995). Burning heavy litter can increase visibility of target plants for spot spraying and is presumed to allow more chemical of soil residual herbicides to reach the root zone (Winter 1993).

Late-summer burning was used to remove litter and thus increase soil contact of pre-emergence grass herbicides in California rangelands dominated by medusahead and barbed goatgrass (*Aegilops triuncialis*) (McKell et al. 1959; Torell et al. 1961). The pre-spray burning was also suggested as providing a benefit by concentrating weed seed, previously held in the litter layer, at the ground surface where it would germinate and be susceptible to the herbicide. Burning downy brome stands before applying imazapic (Plateau®) herbicide pre-emergence can increase efficacy and lower the herbicide rate required for good control (Vollmer and Vollmer 2004, personal communication). The greater the amount of plant residue or litter, the higher the rate of imazapic needed for sufficient herbicide to reach the soil to control emerging brome seedlings.

Other benefits of site preparation burns

Early spring burning has been suggested to remove litter and speed emergence so it is easier to find wild parsnip (*Pastinaca sativa*) rosettes so they can be dug out (Eckardt 1987).

In wetland weed management, top-killing plants with fire before flooding allows water to cover resprouts and thus suppress regrowth. Examples are burning saltcedar along the Rio Grande prior to flooding (Friederici 1995) and Bahia grass (*Paspalum notatum*) in Florida (Van Horn et al. 1995).

Herbicides may be applied before a prescribed burn to facilitate desiccation and increase flammability of exotics that can be difficult to burn such as gorse (*Ulex europaeus*) (Rolston and Talbot 1980).

Debris Burns

Site cleanup

Although giant reed (*Arundo donax*) is highly adapted to fire and tends to increase fire frequency and intensity, burning is sometimes used to remove dead biomass after herbicide treatment or cutting so other species can occupy the site (Bell 1997; Dudley 2003).

Burn out resprouting stumps or roots

Cut, chained, or root-plowed debris from saltcedar stands is often piled before burning to prevent resprouting from adventitious buds (Taylor and McDaniel 1998). The pile burns are usually more effective than broadcast burning.

Stimulate Desirable Competitors

It has been suggested that repeat annual burning of leafy-spurge-infested tallgrass prairie in mid-spring may help suppress leafy spurge and promote these native grasses at least in conjunction with herbicide treatments (Masters 1992; Masters and Nissen 1998). A major benefit of burning tallgrass prairie infested with cool-season grasses is that the thatch removal increases the early growth rate and vigor of the native warm-season grasses because of solar heating of the soil (Ehrenreich 1959).

LIMITATIONS ON TACTICS

D'Antonio et al. (2003) state: "Fire intensity can be manipulated to some extent by season of burn and pre-treatments that influence fuel load (including intensive grazing to reduce fuel or rest from grazing to increase fuel), and by ignition strategies (i.e., using a headfire [driven by wind] versus a backing fire [burning into the wind]). Intensity is also influenced by factors that cannot be controlled, such as slope, soil texture, and humidity and temperature (Daubenmire 1968). Controlled burns tend to be less intense than wildfires, and small fires less intense than large fires."

Fire Severity

Seeds in or near the soil surface are seldom damaged by the flames of grassland fires (Daubenmire 1968b; Vogl 1974). Fuel distribution in shrublands varies with the vertical and horizontal canopy structure. The subsequent impact of a shrubland burn on plants and seeds can have high small-scale spatial variability (Brooks 2002; Evans and Young 1987; Young and Evans 1978).

Seasonal Timing

The optimal phenological timing for impacting the target weed is often outside the parameters for which a burn permit will be issued, or requires suppression capability that strains the manager's resources (Pendergrass et al. 1988; Pollak and Kan 1998). It may be possible to manage both exotic grasses and woody species in fire-adapted southeastern ecosystems by precise timing of burns during the lightning-caused-fire season (Platt and Stanton 2003).

Phenology of Multiple Targets

Blankespoor (1987) was able to use late-spring burning to suppress Kentucky bluegrass (*Poa pratensis*), but co-dominant smooth brome (*Bromus inermis*) was not reduced because its tillers do not elongate into the fuel bed until several weeks or more after the Kentucky bluegrass growing points are susceptible. Old (1969) noted the same separation in optimal phenological timing when he was able to nearly eliminate Kentucky bluegrass by late-April burning but only slightly reduce smooth brome. Becker (1989) found that the optimal timing for repeat burning to suppress Kentucky bluegrass did not reduce quackgrass (*Agropyron repens*) canopy cover because of the relatively later tiller elongation of the quackgrass. An optimally timed burn for one target may result in increases of other exotics with different phenologies (Murphy and Lusk 1961).

Fine Fuel Availability

Managers observe that invasive forbs and trees can reduce the amount and continuity of fine fuels (Abella 2001). The change in fuel characteristics at the later stages of invasion limits the opportunities for effective but still safe prescribed burns (Xanthopoulos 1986). The potential to use fire as part of an integrated control strategy may also be lost at advanced stages of invasion because the altered fuel structure will not carry a fire (Glass 1991; Grace 1998). Spraying yellow starthistle the year before burning could increase fine fuels from annual grasses and the effectiveness of the burn (DiTomaso 2001).

Straw may be added to degraded tallgrass prairie sites to facilitate initial-year burning of cool-season exotic grass if the treatment areas are small (Schramm 1978). There is an anticipation that responding warm-season grasses will provide adequate fuel in succeeding years. In low-productivity ecosystems it may take several years of litter and standing dead accumulation before there is sufficient fine fuel to carry an effective fire (DiTomaso et al. 2001).

Complex Terrain and Phenological Stage

Fire may be uniformly applied to large areas of annual grasses in the Great Basin, but plants of a single target species reach a given phenological stage on different dates in complex terrain.

Frequency

Annual burning of tallgrass prairie greatly suppresses exotic species richness and abundance while stimulating the native C_4 grasses (Smith and Knapp 1999; Smith and Knapp 2001). However, most ecosystems did not evolve with natural fire frequencies as high as that of tallgrass prairies. Fire frequency high enough to suppress target weeds in many ecosystems may exceed the natural regime and thus have undesirable longer-term impacts on native species composition. This suggests to some that other control methods need to be used in some years between burning (Kyser and DiTomaso 2002).

Human Constraints (Smoke, Containment)

Air quality regulations are restricting the use of prescribed fire even for grassland ecosystems (McPherson 1995). Spring burning is prohibited on many wildlife refuges because of impacts on nesting birds. Burning parts of the refuge on a yearly basis can be beneficial to nesting birds. Increasing residential construction and roads adjoining wildland areas are constraining the use of prescribed fire as a vegetation management tool.

DETAILED CASE STUDIES

Annual Grasses & Forbs

Vertical and horizontal canopy structure and fuel load strongly affect heating patterns and seed mortality in shrublands. Differences in peak temperature cause spatial variation in control and succession of annual exotics in California creosote bush (*Larrea tridentata*) in the Mojave desert (Brooks 2002). These desert shrublands are infested with numerous exotic annuals, bromes [primarily foxtail brome (*Bromus rubens*)], Mediterranean grasses (*Schismus* spp.), and redstem filaree (*Erodium cicutarium*). Sites were burned in spring and summer. Flame length varied from 4 in (10 cm) at interspace positions to 102 in (260 cm) within creosote bush canopies. Burn temperatures under creosote bush canopy were high enough to kill exotic annual seeds belowground as well as aboveground. The exotics remained suppressed for four years. At the shrub canopy drip line, lethal temperatures were reached only aboveground, annual exotics were suppressed for only one year, and by the third year Mediterranean grasses and redstem filaree had increased. The burns had little effect on the interspaces. The investigator concluded that fire can temporarily reduce foxtail brome and may allow reseeded natives to establish, but Mediterranean grasses may quickly increase.

A competition study of the perennial native purple needlegrass (*Nassella pulchra*) and exotic annual grasses in the California Central Valley grasslands included grazing and burn treatments (Dyer and Rice 1997). The burns were made in early September when all the grasses were senescent. The investigators concluded that although burning has the potential to favor the native perennial, unfavorable conditions were not created for the exotic annuals by the late-summer burn timing.

An early report (Furbush 1953) stated that burning medusahead in California in early June when other annual grasses had cured but the medusahead seed was still in the milk to early dough stage provided good control for at least three years. However, the benefit may be patchy from some burns. Medusahead seeds were collected after a June burn in California (Sharp et al. 1957). Germination was zero from seeds for which the awns were consumed and the lemma tips charred. Germination was 87% from uncharred seeds although the fire had consumed the culm up to the seedhead.

Other annual exotics increase after well-timed and effective medusahead burns. Examples are broadleaf filaree (*Erodium botrys*), which disperses its seed in early spring, and soft brome (*Bromus hordeaceus*), which shatters while medusahead seeds are still green (Murphy and Lusk 1961). Soft brome is more desirable for livestock forage than medusahead. After a single prescribed fire, very little medusahead was present on a treated site in another California trial (DiTomaso et al. 2003). A June 28 burn greatly reduced medusahead a year later in a Central Valley experimental pasture (Pollak and Kan 1998). Native grasses as well as exotic and native forbs increased in this pasture. Medusahead matures later in the spring than most associated species, and has a seedhead moisture content of above 30% for approximately a month after leaves and stems begin to dry (McKell et al. 1962). High temperature was proven to be more injurious to seed viability when seed moisture content was high. Medusahead seed germination decreases as fire intensity or fuel loads increase

(Murphy and Turner 1959). Controlled burns of medusahead-infested California rangeland were most effective in late afternoon when conducting a backing fire under mild wind, and at the soft dough stage of medusahead seed development. Fuel loads averaged 5,200 lbs/ac (5,828 kg/ha) in the Mckell et al. (1962) experimental burns.

One, two, and three successive summer (July-August) burns were used in medusahead-dominated native perennial grass stands in cismontane northwestern California (Young et al. 1972). A backing fire (2 to 3 ft/min or 0.6 to 0.9 m/min) with 1.5-ft (0.5-m) flame height was used the first year and it removed the standing herbage and scorched the litter in contact with the soil. Less fuel and increased poverty weed (*Iva axilla*) with green succulent leaves prevented the second- and third-year fires from carrying well and necessitated head fires. Medusahead seeds were in the late soft dough stage when the burning was done. The stand burned once had an initial increase in medusahead canopy cover, but it returned to a level similar to the control by the third year. There were significant medusahead increases after two and three years of successive burning. The perennial grasses at about 5% cover did not benefit because the medusahead, at 68 to 86% post-burn cover, was not suppressed. Downy brome, much less abundant (about 15% initial cover) than medusahead, declined with repeat burning even though these seeds had dropped to the ground before the burns. The investigators suggested that the burning gave medusahead a competitive advantage over downy brome.

A failed attempt was made to suppress medusahead and downy brome in an Oregon native bunchgrass biscuit-scabland habitat by spring burning in an initial year, followed by two years of glyphosate spraying or frequent mowing (Ponzetti 1997; Youtie 1997; Youtie et al. 1998). The burn was delayed until July 6 when the downy brome had begun to shatter and some of the medusahead was in an early kernel stage. Fire intensity was moderate with flame lengths of 1 to 3 ft (0.3 to 0.9 m). Although most of the medusahead seeds were consumed or charred, a small percentage were unburned and the litter was generally intact. The burning caused 15 to 18% bunchgrass mortality as these native species were actively growing at the time of the burn. Effects of the added herbicide or the mowing treatments were similar. Initially about one-third of the treatment area showed a decrease in annual grass abundance. These were the areas with the highest initial abundance of medusahead and downy brome. The total treatment area infested with medusahead increased at a rate similar to the untreated control area. The initial suppression observed in some areas was temporary and both annual grasses reverted to pretreatment levels after several years. The BLM in central Oregon has reported success in suppressing medusahead by late-spring to early-summer burning while the seed is still on the culms, glyphosate treatment (0.375 lbs/ac or 0.420 kg/ha) the next spring after remnant medusahead seeds have germinated, then reseeding with desirable grasses and shrubs (Miller et al. 1999).

Barbed goatgrass (*Aegilops triuncialis*) is invasive of even undisturbed grasslands in California (DiTomaso et al. 2001). Development rate of this winter annual can vary greatly depending on precipitation patterns. Optimal timing of burning is after desirable plants have senesced but before goatgrass seeds are fully mature and these soft seeds are still in the inflorescences. The optimum phenological burn dates in this study ranged from early May to early July. The pastures were burned in two years.

Sufficient fuels were available the first year for burning 100% of the pasture areas. In the second year, the fuel load was not high enough for a complete burn in all three pastures. The second year, burned areas ranged from 75 to 100%. Barbed goatgrass seedbanks were greatly reduced after two years of burning, but the reduction correlated exactly with the completeness of the burns in the second year. Barbed goatgrass canopy cover did not decline significantly in the first year post burn, but in the year after the second burn the cover was reduced in proportion to the completeness of the area burned. Several natives increased in the burned pastures. The plant community was resampled three years after the last burn. The pastures that had obtained more complete second-year burns still had good suppression of barbed goatgrass and improved native perennial grasses.

Early summer burning of barbed goatgrass in central California, when the seeds were still in the inflorescences, reduced cover but not spread (Hopkinson et al. 1999). Cover in burn plots was reduced by approximately half, but infested acreage increased tenfold in three years. One of the two experimental burns was in July. The precise stage of seed maturation on the burn dates was not specified.

Jointed goatgrass (*Aegilops cylindrica*) is primarily a pest of small grain crops, but infests roadsides and has some capability to invade rangelands. Seed germination was reduced 72% by Bunsen burner flaming for one second and completely suppressed by a three-second exposure (Willis et al. 1988). Germination began to decrease at oven temperatures of 302°F (150°C) for 20 seconds and was completely stopped by a 120-second exposure. Temperatures of 392 to 752°F (200 to 400°C) for 120 seconds reduced germination 50 to 100% in a second oven test (Young et al. 1990). Wheat field burning destroyed enough seed or killed enough embryos in spikelets suspended in litter and at the soil surface to suggest post-harvest burning could suppress jointed goatgrass density in agricultural fields. Fuel loads in these wheat fields were very high (8,386 to 12,937 lbs/ac or 9,400 to 14,500 kg/ha) and some included supplemental straw.

Annual grassland pastures in the California Central Valley were burned in August to October because the mulch layer was driest at those times, but cooler temperatures and higher relative humidity facilitated control of the fires (Hansen 1986). Many of the burns reduced native and exotic annual grasses but increased native forbs and exotic annual forbs such as redstem filaree. Mulch coverage of the soil favored germination and establishment of the exotic grasses, while some forbs had seed burial mechanisms (lacking in the annual grasses) that were effective on bare soil. Others have demonstrated that mulch facilitates germination and vigorous growth of exotic annual grasses in California (Heady 1956). Removal of the mulch layer by fire or other methods retards germination and seedling establishment of downy brome and soft brome (*Bromus hordeaceus*) in California annual grasslands (Smith 1970).

Late spring, fall, and winter burning plus a mechanical mulch reduction treatment to simulate grazing were applied to California Central Valley annual grassland plots (Meyer and Schiffman 1999). The site was dominated by foxtail brome (*Bromus rubens*), hare barley (*Hordeum murinum*), barbed oat (*Avena barbata*), and wild oat (*Avena fatua*). The late-spring burn was most effective in suppressing the exotic grasses and promoting native forb species in the growing season after the treatments. The fall burn (late September) was also effective. The winter burn (after exotic grasses had emerged) and the mulch reduction treatment reduced exotic grass cover less than the two warm-season burns and did not provide any increase in native forbs. The warm-season fires were most beneficial because of differential phenology of exotic and native species, higher fire intensity, and removal of almost all the mulch. The investigators caution that the optimal date for implementing a late-spring burn is highly dependent on rainfall, which controls seed set of the annual grasses. These exotic annual grasses returned to pretreatment dominance while native forbs were rare by the second growing season after burning.

Fall or spring burns were applied for one, two, and three successive years to exotic-annual-grass-dominated sites in Sequoia National Park of central California (Parsons and DeBenedetti 1984; Parsons and Stohlgren 1989). Treatments were not replicated. Spring conditions were hotter and drier than the fall. Spring burns were early to mid-June when the annuals were dried out but before the natural fire season. Flame lengths were 2 to 5 ft (0.6 to 1.5 m) and spread rates were 13 to 66 ft/min (4.0 to 20 m/min). The fall burns were done in late October or early November and had flame lengths of 1 to 3.3 ft (0.6 to 1.0 m) and spread rates of 8.2 to 16.4 ft/min (2.5 to 5.0 m/min). Three successive fall burns decreased the biomass and frequency of exotic annual grasses, but changes following one or two burns were transitory. Spring burns were less effective than fall. Species richness in small plots almost doubled with the three-year fall sequence because of an increase in exotic and native annual forbs. The burn-induced shifts included increased abundance of Malta starthisle (*Centaurea melitensis*), a noxious exotic annual forb that was not found in the pre-burn sampling and remained rare in the control plots. No native grasses established during the study.

Community response to one to three successive years of spring or fall burning of annual grassland in a nature preserve in southern California was examined (Wills 2000). The data were not presented, but the author reported that spring burns reduced abundance of exotic grasses and some native forbs while increasing biomass of native perennial grass. The preserve included stands that still had good cover of native perennial grasses and these had more benefit from burning. Short fire return intervals reduced the annual grass cover and thatch build-up, but may have contributed to the native forb decline. Fall burns increased exotic grass biomass in contrast to the Parsons (1984, 1989) central California studies where fall burning decreased annual grasses. The Wills (2000) responses were not maintained when burning was discontinued.

A review of 28 studies and meta-analysis of 19 data sets on the response to burning and grazing of California grasslands indicated that prescribed burning temporarily reduced the exotic annual grasses, but also resulted in increased exotic forbs as well as native forbs (Bainbridge and D'Antonio 2003; D'Antonio et al. 2003). Single burns often decreased the exotic annual grasses, but they recovered by the third year. Grazing or follow-up burns retarded the recovery of the exotic annual grasses and maintained the forb cover. The burning did not tend to benefit the remnant native perennial grasses and tended to have an initial negative effect.

Downy brome seed under the shrub canopy can be destroyed by the heat generated by the woody fuel (Young and Evans 1978), but these areas must be planted with desirable species the year of the fire or they will be reinvaded by new downy brome seeds generated in the shrub interspaces where the herbaceous fuels alone could not deplete the downy brome seedbank (Evans and Young 1987). Burning downy brome, particularly in downy brome-dominated sagebrush steppe, is most useful as a seedbed preparation technique followed by seeding desirable species (Rasmussen 1994).

Japanese brome (*Bromus japonicus*) in South Dakota mixed-grass prairie was suppressed in the year following either fall or spring burns (Gartner 1975). The burns were set as headfires with 4,000 to 5,000 lbs/ac (4,483 to 5,604 kg/ha) of fuel. The spring burning was followed by increased production of western wheatgrass (*Agropyron smithii*), a native rhizomatous perennial. The same principal investigator (Gartner et al. 1979) observed similar results after late-winter or early-spring strip-burning at several additional South Dakota mixed-prairie sites. High suppression of Japanese brome was measured through the second growing season post burn in this study. Burning can cause direct mortality to emerged seedlings of this winter annual. Japanese brome retains its seed in the inflorescence for an extended period compared to downy brome. Japanese brome in unploughed tallgrass prairie in Kansas increased over time since last burning of different areas of the preserve (Gibson and Hulbert 1987).

Three-by-three-meter-square plots of blue grama (*Bouteloua gracilis*)-dominated mixed-grass prairie in eastern Montana were burned in early October or early to mid-April while native species were dormant (White and Currie 1983). Downy brome and Japanese brome were codominants in these stands. The fall burn timing caused a 70% annual brome reduction relative to the controls in the growing season after the burn, and the spring burn had a 50 to 60% reduction. Mixed-grass prairie responses to season of burning were measured in Nebraska (Wendtland 1993). It was reported that annual grasses (*B. tectorum* and *B. japonicus*) generally decreased for two years after summer or fall burns, but spring burning was ineffective; however, the inferences are weak because of design and drought problems. These decreases were attributed to seed destruction and removal of the litter layer reducing germination success.

Native cool-season perennial Texas wintergrass (*Stipa leucotricha*) stands containing Japanese brome were burned in October, January, or March after the winter annual seedlings had emerged (Whisenant et al. 1984). Fine fuel loads were 2,500 to 3,000 lbs/ac (2,802 to 3,363 kg/ha) with 9 to 13% fuel water. Japanese brome standing crop in the first growing season after the March burn was 31 lbs/ac (35 kg/ha) compared to 212 lbs/ac (238 kg/ha) on the unburned controls. Japanese brome standing crop was only half that of controls in the second year after the March burn, but the suppression was not statistically significant.

Japanese brome response to one-time April burns in a western South Dakota mixed-grass prairie was reported for two years after burning (Whisenant and Bulsiewicz 1986), and a subset of these plots was followed for four and five years after (Whisenant 1990; Whisenant and Uresk 1990). One-time burning treatments were done in two different years in mid-April when the Japanese brome seedlings were 3 to 5 cm tall. A 1983 burn had 1,882 lbs/ac (2,110 kg/ha) of fine fuel with 18% fuel water and a 1984 treatment had 2,462 lbs/ac (2,760 kg/ha) of fine fuel with 23% fuel water. Litter consumption by the 1983 fire was 95%, and 92% by the 1984 burn.

The fires reduced density and seed production in the first growing season after the burns. In the second post-burn growing season, density had returned to pre-burn levels. Seed production was still half of controls, but the number of seeds formed in the previously burned plots was very large [4,333/ft^2 (46,644/m^2)] and the soil seed bank had been fully replenished. Seed production remained depressed for at least three years. Recovery rate was controlled by fall precipitation, allowing germination of this winter annual and new litter accumulation which promotes germination. Differences of one or two years control reported by different studies can thus be explained by post-burn fall precipitation with new litter accumulation contributing more to germination success in drier years. That is, burning will provide only one year of good control unless the burn is followed by a droughty fall. Half of the 1983 plots were burned a second time in April 1984 when available fine fuel was only 1,240 lbs/ac (1,390 kg/ha) with 20% fuel water (Whisenant and Uresk 1990). The second fire did not carry well and the Japanese brome density in 1984 was greater on the plots burned twice than those burned only once in 1984.

Multiyear annual prescribed burning has been used in California to suppress yellow starthistle abundance and nearly deplete the soil seedbank (Hastings and DiTomaso 1996; DiTomaso et al. 1999). Phenological timing was the very early flowering stage of the yellow starthistle in early July when the grasses were cured and most of the desirable species had dropped their seed. The backing fires produced 2- to 4.9-ft (0.6- to 1.5-m) flame lengths. The soil surface temperatures of the various yearly burns ranged from 300 to 572°F (149 to 302°C). Greenhouse germination tests of seeds collected from the soil surface confirmed that seed mortality was not a factor, but the burns caused nearly complete yellow starthistle mortality, which prevented new seed formation. After three years of burning, the seedbank and seedling density had been reduced 99% and the summer canopy cover was reduced by 91%. Native plant diversity and perennial grasses increased. Treatments were stopped in the fourth year and the yellow starthistle seedbank increased 30-fold that year (DiTomaso and Gerlach 2000). The yellow starthistle seedbank continued to rise dramatically during four years of measurement after cessation of burning (Kyser and DiTomaso 2002). Yellow starthistle seedling density and summer canopy cover also increased. Other forb cover and plant diversity decreased. By the third year, the plant community had reverted to its unburned condition.

A trial to repetitively burn yellow starthistle and conduct post-burn seeding of potentially competitive natives was begun in 1999 at Pinnacles National Monument in California (Martin and Martin 1999). A sterile wheat-wheatgrass hybrid (Regreen) was seeded after the first burn to supplement fine fuels. However, the project was suspended in 2000 because of concerns about fire containment (T. Leatherman, personal communication).

Winter season flaming of rosettes was tested for yellow starthistle control in east-central California (Rusmore 1996). Control was good in a dry winter but inadequate under wet winter conditions so the technique was discontinued.

Biennial Forbs

In the Midwest, white sweet clover (*Melilotus alba*) and yellow sweet clover (*Melilotus officinalis*) in even-aged stands is often controlled by a two-burn sequence

(Cole 1991; Kline 1983; Kline 1984). A hot April burn in the first year scarifies seed and stimulates germination. A second-year burn in May kills the biennials before they finish bolting and replenish the seedbank. The first burn could be in late fall rather than April. If the infestation was heavy and the seedbank well-developed, the two-burn sequence may have to be repeated, leaving a two-year no-burn period between each series of two burns. This was the most effective burn treatment sequence in a Wisconsin tallgrass prairie study (Kline 1983). In uneven-age stands, the treatments may be less effective because some second-year plants escape the early first-year burn and set seed. Implementing the initial burn somewhat later in the spring could overcome this second-year plant susceptibility problem with uneven-aged stands. An initial late-spring (April 30) burn timed to reduce cool-season exotic grasses in an eastern South Dakota tallgrass prairie also caused an increase in germination and resultant biomass of sweet clover (*Melilotus* sp.), but then a decrease was measured after a second-year late-spring burn (Blankespoor 1987). The switch in meristematic activity from the crown buds in first-year plants to aboveground lower stem in second-year plants makes these bolting plants susceptible to fire mortality (Heitlinger 1975). The phenological timing suggested for second-year sweet clover burning by Heitlinger (1975) was refined by a study done on a planted tallgrass prairie site in southern Wisconsin (Schwarzmeier 1984). Plots burned on May 18 had only 4.8% sweet clover cover in July compared to 90.9% on controls. Optimal burn timing is seven to 10 days after sweet clover stem bases were fully shaded below 5 in (13 cm). In recently planted tallgrass stands, a lack of thatch or green growth >75% in the fuel layer can reduce fire intensity, so these should be burned five days after the suggested full-shade point.

A vegetation analysis was done of a number of tallgrass prairie sites in the southeast corner of North Dakota that were burned in May or June on one or two years (Olson 1975). Some of these sites had sweet clover, but the burn schedules were not chosen to specifically suppress sweet clover. However, as in the Midwest, there was increased germination in the first post-burn growing season and complete mortality of second-year plants burned in June.

Several burning prescriptions were tested for suppression of garlic mustard (*Alliaria petiolata*) in an Illinois upland oak forest (Nuzzo 1991). Spring and fall burns were conducted at mid and low intensities and some plots were burned twice. There was no replication of the treatments. Oak leaves were the primary fuel in this low surface fuel load ecosystem. Mid-intensity burns had flame lengths up to 6 in (15 cm) and good area coverage. The low-intensity burns had maximum flame lengths of only 1 in (3 cm) and the fire frequently died when it reached areas with high coverage of garlic mustard rosettes. Mid-intensity spring fires reduced garlic mustard rosette density and seedling frequency, but fall burns only impacted rosette density. The low-intensity burns were all ineffective. Garlic mustard remained a major herbaceous component even where reduced by these limited burn treatments. Burning was repeated for three years on two plots in another Illinois oak forest (Nuzzo et al. 1996). Most of these sequential burns were in the spring. All the fires were hot and fast with flame lengths of up to 4 ft (1.2 m), and 95 to 100% of the plot areas were burned. Garlic mustard increased after the first fire by resprouting from root crowns under the damp lower litter layer. Removal of leaf litter enhanced survival of seedlings that germinated after the fire. But the sequential burns suppressed the garlic mustard to 1.5 to 2.4% cover while it doubled every two years to 17% cover on the unburned control.

A northern Illinois dry-mesic upland forest, where slippery elm (*Ulmus rubra*) and northern white oak (*Quercus alba*) had the highest importance values, was burned in an attempt to suppress garlic mustard (Schwartz and Heim 1996). Single five-acre (2-ha) tracts were burned during the dormant season (early March) or during the early growing season (May). The dormant-season burn was of low to moderate intensity with 0.5- to 3.3-ft (0.15- to 1.0-m) flame lengths, a 4.3 ft/min (1.3 m/min) spread rate, and it burned 75 to 80% of the unit. The growing-season burn was of moderate intensity with 4- to 30-in (10- to 75-cm) flame lengths, a 5.6 ft/min (1.7 m/min) spread rate, and it burned 75 to 80% of this second unit. Garlic mustard cover declined on all units, including the control, in the two years after the fire, then resurged in the third year. The decline was greatest on the growing-season burn unit. However, declines in the native herbaceous layer were also most severe in the growing-season burn unit. The investigators suggested a burn in the narrow window between the dormant season. Initiation of growth by native herbaceous species may significantly reduce this winter biennial without adverse effects on the natives. However, implementing such early-spring burn timing at a larger scale would be difficult in this ecosystem, and repeat burning and/or incorporation of other methods would be required to suppress garlic mustard.

Repeated fall dormant-season burning was tested for suppressing garlic mustard in a northern Kentucky woodland understory (Luken and Shea 2000). One set of plots was burned for three years and another set for two years. The plots were burned going upslope with 6-in (15-cm) flame lengths. These repeated dormant-season burn treatments did not reduce the abundance nor relative importance of the garlic mustard. It has been stated that herbicide treatments combined with burning have been the most effective approach for suppressing garlic mustard, so replicated trials have been initiated to test this integrated approach (Martin and Parker 2003).

Perennial Grasses

A large body of literature confirms that mid- to late-spring burning of tallgrass prairie is an effective technique to reduce the prevalence of nonnative cool-season grasses and promote warm-season native grasses. The optimal timing is when the tillers are elongating on the cool-season grasses but the warm-season natives are still dormant. Increasing the frequency of these spring burns increases the suppression of the nonnative grasses.

An early study reported the decline in exotic cool-season grasses on Wisconsin sites subjected to annual or biennial burns over a six-year period (Curtis and Partch 1948). March, May, and October timings were used on these Kentucky and Canada bluegrass (*Poa pratensis* and *P. compressa*)-dominated sites. All the burn treatments reduced exotic grass density to as little as one-fifth, but the May burns were most effective. Planted big bluestem (*Andropogon gerardii*) was among the native species that increased. Kentucky bluegrass canopy cover in eastern Kansas tallgrass prairie was greatly reduced by April burning (Abrams 1988). Kentucky bluegrass canopy cover was 30% on unburned sites, 7% on sites burned every four years, and was zero on sites burned every year. The elimination of Kentucky bluegrass canopy cover by annual burning was measured for upland and lowland sites (Abrams and Hulbert 1987). The annual burns began in 1972 and 1978, respectively, and the reported canopy cover results were for 1984. The historic fire frequency since the mid-1800s was estimated as being every two to three years.

A burning program was sustained for 36 years in a Kansas tallgrass prairie except for one six-year suspension (McMurphy and Anderson 1965). Winter (~1 December), early spring (~ 20 March), mid-spring (~10 April), and late-spring (~1 May) burns were done on annual and biennial schedules. All burn schedules held Kentucky bluegrass to less than 0.5% of the plant cover in ungrazed plots while unburned controls had 6.4%. The exotic annual Japanese brome cover was 1% or less on the burn plots compared to 2.9% on the check plots. The same study sites were re-appraised after 56 years of near annual burning (Towne and Owensby 1984). The longer-term analysis confirmed the near elimination of Kentucky bluegrass and demonstrated that the closer the burn date was to the initiation of spring growth by little bluestem (*Schizachyrium scoparium*), the bigger the benefit as measured by increases in total basal cover of warm-season natives. The early- to mid-spring burn dates were most favorable.

Watershed units of tallgrass prairie in eastern Kansas that were burned annually for 15 years had lower frequency and much lower cover and richness of exotic plants than unburned watersheds (Smith and Knapp 1999). Exotic forbs and annual and perennial cool-season grasses (including Kentucky bluegrass) were suppressed or absent from the burned watersheds. Exotic plant cover averaged 0.013% in the watersheds with the long-term annual burn regime and 22.8% in the unburned watersheds. Higher fire frequencies in watersheds managed over a 27-year period correlated with decreasing richness of exotics. These high-frequency burn regimes strongly favored C_4 natives over predominantly C_3 exotics.

Test plots on a tallgrass prairie site in northeast Iowa were burned as frequently as annually over a three-year period (Ehrenreich 1959). The burns were always about the first of March. Kentucky bluegrass declined and warm-season grasses increased. The shift was attributed to some direct injury to Kentucky bluegrass and earlier and more vigorous growth of the warm-season grasses because litter removal increased soil temperature. A Kentucky bluegrass-dominated tallgrass prairie remnant in Iowa was burned once on April 10 (Hill and Platt 1975). Kentucky bluegrass averaged 517 lbs/ac (580 kg/ha) at peak biomass on the burned plots and 1,918 lbs/ac (2,150 kg/ha) on the unburned plots in the first summer after the burn. Dominance shifted from Kentucky bluegrass to big bluestem (*Andropogon gerardii*).

Late-spring burns were used in trials to establish native grasses by planting seed into abandoned Wisconsin fields dominated by exotic bluegrass (*P. pratensis* and *P. compressa*) sod (Robocker and Miller 1955). Two successive years of spring burns were timed to suppress the actively growing bluegrass prior to dormancy break of the warm-season natives. Increases in density of warm-season grass species on the burn plots were attributed to reduction in competition from bluegrass.

A single late-April burn in an Illinois tallgrass prairie effectively eliminated Kentucky bluegrass in the growing season following the burn and significantly reduced the biomass of smooth brome (*Bromus inermis*) (Old 1969). The first-year suppression was attributed to the direct effect of the fire. The differential species response was attributed to the different phenology of these two exotics. Smooth brome does not begin growth until mid-April and peaks in mid-July, but the Kentucky bluegrass begins in early April and peaks by mid-May. Kentucky bluegrass was severely damaged by the late-April burn, but smooth brome was just inhibited. Competition of both exotics with the warm-season natives was reduced.

Smooth brome tiller elongation elevates the growing point to a height where it is susceptible to substantial direct injury from grassland fires. Smooth brome plots in Nebraska were burned by backing fires at three different stages of growth: tiller emergence (late March), tiller elongation (mid May), and heading (late May) (Willson 1992). Most of the litter was removed by the fires. The burns at the tiller elongation and heading stages reduced smooth brome tiller density by 50% relative to controls in the fall after the burns. Most northern prairie managers tend to burn earlier than the optimum timing for smooth brome suppression. The May burns used in this study were smokey, but the fire carried well in spite of the green biomass. Codominant big bluestem was enhanced by these burn timings. The actual dates need to be adjusted for latitudinal shifts in smooth brome phenology. The five-or-more-leaf stage was suggested as the optimal timing. The initial study was extended to allow for repeat burning of the same sites in consecutive years and consideration of burns at the flowering stage (mid-June) (Willson and Stubbendieck 1997). Burning at the flowering stage also suppressed smooth brome. Single burns at any timing allowed partial to full recovery in the following year. Repeat burning at tiller elongation was most effective in maintaining low smooth brome abundance. The optimal phenological timing -- tiller elongation -- was used for selecting late-May burn dates on two years (different plots) at a southwestern Minnesota site (Willson and Stubbendieck 1996). These two backing fires only reduced smooth brome densities by 16% and 37% -- nonsignificant results. The lower suppression in this Minnesota study was attributed to a lack of warm-season grasses compared to their co-dominance at the Nebraska site. Secondary tiller growth by smooth brome, in the absence of warm-season grass competition, allowed the smooth brome to recover. Wilson and Stubbendieck have used their experimental experience to develop a burning decision model for smooth brome suppression in tallgrass prairie (Willson and Stubbendieck 2000).

A single spring (mid-April) headfire under moist litter conditions was applied to an Iowa tallgrass prairie site (Richards and Landers 1973). The Kentucky bluegrass had begun growth before the burn. The burn significantly reduced yield and flowering of Kentucky bluegrass in the following growing season. Flowering was also significantly inhibited for creeping bentgrass (*Agrostis stolonifera*) and timothy (*Phleum pratense*). Bentgrass was designated a decreaser after a single spring burning in a western Washington oak woodland and based on a decline in frequency of occurrence from 79% to 59% using 10.7-ft^2 (1-m^2) microplots (Tveten and Fonda 1999). However, this shift was not significant.

Kentucky bluegrass in unploughed tallgrass prairie in Kansas increased over time since last burning of different areas of the preserve that received early spring fires at various frequencies (Gibson and Hulbert 1987). The burns were before the green-up of warm-season grasses which benefited from the fires. Forbs declined with the high fire frequencies in this ecosystem. Kentucky bluegrass and smooth brome abundance were lowest in annually burned plots in another detailed analysis of prescribed fire regimes in this preserve (Gibson et al. 1993).

Kentucky bluegrass was less prevalent in northeast Kansas tallgrass prairie that was being burned annually in April than sites that were burned every four years (Hartnett et al. 1996). Bison grazing on lowland sites significantly increased Kentucky bluegrass relative to ungrazed sites burned on a four-year cycle, but grazing under the annual burn cycle did not facilitate a significant increase in Kentucky bluegrass.

Native tallgrass big bluestem (*Andropogon gerardii*) prairie in eastern Nebraska was subjected to a single late-April burn (Hover and Bragg 1981). Kentucky bluegrass was at low cover values (≤2%) and declined even further in the first growing season after the burn in comparison to mowed control plots. Kentucky bluegrass was also just a minor component in a high-quality big bluestem tallgrass prairie in Kansas where an experiment was conducted to determine why burning increased production and flowering of the native grasses (Hulbert 1988). Tabular data indicated that Kentucky bluegrass biomass was lowest on burned plots.

A degraded prairie site in southwest Minnesota was burned annually for five years (Becker 1989). The grassland types were short- and mid-grasses on shallow soils and tallgrass prairie on deeper soil. Cool-season exotic grasses had invaded the preserve. The burns were conducted in mid-April to early May when the cool-season exotic grasses were 4 to 10 in (10 to 25 cm) in height. Fire intensity was low to moderate except for the first burn, which had more fuel. Over the five years of treatment, the burns increased the cover of the native warm-season grasses and forbs. Kentucky bluegrass canopy cover declined with the high-frequency burning. Although the early-spring burning reduced the height and flowering of quackgrass, the prescription did not reduce quackgrass canopy cover. Quackgrass tillers elongate later than Kentucky bluegrass, so the fire probably had less impact on quackgrass because of the phenologic timing. A mid-May backing fire reduced the first growing season post-burn biomass of quackgrass, prevented flowering, and also caused some reduction in quackgrass frequency in a prairie-oak savanna area in eastern Wisconsin (Diboll 1986). The site had an 8- to 12-in (20- to 30-cm)-deep mulch layer and the backing fire resulted in 54 lbs/ac (60 kg/ha) of litter left on the burn plots in July compared to 8,306 lbs/ac (9,310 kg/ha) on the control.

Near annual burns were made on test plots in a high-quality prairie remnant in southcentral Wisconsin (Henderson 1992). Timings were early spring (late March to early April), late spring (mid-May), or late fall (mid-November to early December). Kentucky bluegrass abundance was significantly reduced at all three seasonal timings with these annual burn regimes. Percent decline, based on frequency of occurrence, was 100% with late-spring timing, 81% with early-spring timing, and even 77% from the late-fall burns.

Burning, fertilization, and atrazine treatments were made in the spring to good condition tallgrass prairie sites in eastern Nebraska (Masters et al. 1992). The combined burning and spraying treatments did not suppress the cool-season grasses more than those treatments alone. Kentucky bluegrass, smooth brome, and annual bromes were minor components of these relatively high-quality tallgrass sites.

A vegetation analysis was done for a number of tallgrass prairie sites in the southeast corner of North Dakota that were burned in May or June (Olson 1975). Some sites had been burned twice. Single May or June burns reduced Kentucky bluegrass abundance, but only for one year. On sites with two sequential burns, the Kentucky bluegrass reduction persisted into the second year post-burn. Smooth brome canopy cover was greatly reduced in the first post-burn growing season by the May burns, but recovery was apparent in the second year. Quackgrass canopy cover was reduced by May and June burns in the first growing season post-burn, but density was often greater in the first year and recovery was nearly complete the second year with apparent stimulation occurring on some sites. Crested wheatgrass (*Agropyron cristatum*) was reduced in the first year by a May burn, but it also recovered and was stimulated on some sites. Mixed crested wheatgrass and native grass stands in Saskatchewan were subjected to fall (late-October) or spring (early-April) burning and two phenological timings of wick application of glyphosate (Romo et al. 1994). Burning had no affect on the crested wheatgrass canopy cover.

Annual or biennial spring burns were carried out over a 13-year period in an eastern prairie-aspen forest transition zone in northwestern Minnesota (Svedarsky et al. 1986). Backing fires, timed to when the new growth of Kentucky bluegrass was 4 to 6 in (10 to 15 cm) high, were done in late April to early May. Both fire frequencies reduced Kentucky bluegrass cover from 70% to 35% over the 13-year treatment period. Big bluestem increased threefold and little bluestem (*Schizachyrium scoparium*) fourfold. The investigators noted that the fires burned hotter as bluestem litter replaced the more matted bluegrass litter. The benefits of burning peaked nine to 10 years after starting the burning program. Although recovery was more rapid with the annual burn frequency, the biennial burning was a lower-cost program and allowed better cover for groundnesting birds every other year.

Paired upland and lowland plots in eastern North Dakota were burned on May 8 (Hadley 1970). The study area was a transition zone from tallgrass to mixed-grass prairie. Production was estimated by clipping in August. The upland unburned plot had 184 lbs/ac (206 kg/ha) of *Poa* spp. while the upland burned plot had 85 lbs/ac (95 kg/ha) of *Poa* spp. The lowland unburned plot had 134 lbs/ac (150 kg/ha) of *Poa* spp. while the lowland burned plot had 95 lbs/ac (107 kg/ha) of *Poa* spp.

Mesic mixed-grass prairie, codominated by Kentucky bluegrass and native grasses, on mesic and xeric sites in northcentral South Dakota were burned once in mid-May or mid-June using headfires (Engle and Bultsma 1984). Drought conditions delayed plant emergence, but the Kentucky bluegrass was in a late growth stage on both dates. The mid-May burn preceded emergence of the warm-season grasses. On the mid-June burn date, the warm-season grasses were 2 to 4 in (5 to 10 cm) tall. Response measurements were made in the same summer as the burns and one year later. There were some site differences in response, but overall the mid-May burns gave the best reduction in Kentucky bluegrass production for both years. There was first-year injury to the cool-season native green needlegrass (*Stipa viridula*), but the burning increased warm-season grasses for both years.

A western wheatgrass/needle and thread grass (*Agropyron smithii*/*Stipa comata*) mixed-grass prairie in western South Dakota was burned on April 21 (Gartner et al. 1986). Large amounts of herbaceous fuel were present because of fire suppression and a moderate grazing regime. The strip-headfire under dry conditions consumed most of the mulch. In the first growing season, post-burn Kentucky bluegrass was 1% of the biomass on the burned plots and 25.8% on the controls. In the second growing season post-burn, Kentucky bluegrass was 2.8% of the biomass on the burned plots and 17.1% on the controls. The proportion of western wheatgrass and important short grasses increased.

Nebraska mixed-grass prairie plots with excessive Kentucky bluegrass were burned once in mid-April or once in mid-May (Nagel 1980). In the fall after burning, the Kentucky bluegrass biomass was significantly lower on all burned plots but the suppression was greatest with the May burn. A reduction in Kentucky bluegrass was still evident in the second growing season after the burns, but regrowth was much greater on productive soil sites than shallow soil sites.

Three southern Nebraska mixed-grass prairie sites with 4,760, 4,176, and 6,721 lbs/ac (5,335, 4,681, and 7,533 kg/ha) of fuel were burned by backing fires on April 25 (Schacht and Stubbendieck 1985). Two sites had a mix of warm-season natives and cool-season exotic grasses, Kentucky and Canada bluegrass, Japanese and downy brome. The third site was dominated by Kentucky bluegrass with a small component of western wheatgrass and native warm-season grasses. Relative species composition was determined for two growing seasons following the late-spring prescribed burn. The cool-season exotics were significantly suppressed and warm-season natives increased for two years after the burn at the two sites that had a high pre-burn component of native warm-season grasses. The cool-season component was not suppressed on the more degraded third site.

In the mountains of western Montana, Kentucky bluegrass frequency was reduced 27.5% by a single late-May (May 24) burn in a sagebrush/fescue bunchgrass habitat type (Bushey 1985). The Kentucky bluegrass had not recovered in the second growing season post-burn. The prescribed burn was intended to suppress Douglas fir encroachment. The reported reduction in litter (18.7%) indicates that this was a low-severity spring burn.

May burns producing ground surface temperatures of 248 to 617°F (120 to 325°C) were conducted in Kentucky bluegrass and quackgrass-dominated residential acquisitions at the Indiana Dunes National Lakeshore (Choi and Pavlovic 1994). The burns did not decrease the targets on these exotic-grass-dominated sites.

Late-spring burning was initiated in an eastern South Dakota tallgrass prairie remnant to suppress Kentucky bluegrass and smooth brome (Blankespoor 1987). The April 30, 1982, burn greatly reduced the biomass of Kentucky bluegrass in the first growing season following the burn. However, the smooth brome biomass was not substantially reduced by the initial burn. Smooth brome growth is delayed relative to Kentucky bluegrass, so the investigator suggested it may be necessary to burn later in the spring to suppress smooth brome. The single-year late-spring burn treatments were most effective in reducing Kentucky bluegrass when soil moisture was low; adequate or above-adequate water can compensate for the initial fire-induced biomass reduction (Blankespoor and Bich 1991). Small plots where smooth brome was the only cool-season grass were selected in the same eastern South Dakota tallgrass prairie remnant studied by Blankespoor in his 1987 report. Selected smooth brome plots were burned in late spring (May 9), then some were given supplemental water and other plots had rainfall excluded in the growing season following the burn (Blankespoor and Larson 1994). At the end of the first growing season, smooth brome had declined in burned plots but increased in the unburned plots. Smooth brome was less abundant on the high-water burned plots than the low-water burned plots. The investigators concluded that high soil moisture promoted native warm-season grasses that suppressed smooth brome recovery from the burning. Burn-induced suppression of smooth brome was more effective in plots that had a substantial warm-season grass component.

Single burns of smooth-brome-infested Fescue Prairie in central Saskatchewan did not reduce the exotic rhizomatous perennial (Grilz and Romo 1994). The burns were done in late October and early spring to minimize fire injury to the native bunchgrasses which were dormant at those timings. Spring burning followed by wick application of glyphosate to the smooth brome gave good control, but the herbicide treatment also reduced native species.

A spring burn treatment was included in a factorial trial to convert a monotypic smooth brome (*Bromus inermis*) pasture in eastern Nebraska to native warm-season grasses. The other factorial treatments were spring atrazine, spring drill-seeding of the native grass mix, and glyphosate in the fall preceding the other treatments (Anderson 1994). The smooth brome was green and 3 in (8 cm) tall when burned in late April. The pasture had been grazed the previous year and burned poorly because of low fuel load. The late-April prescribed burning did not suppress smooth brome production nor aid in establishment of the warm-season grasses. However, the investigator stated that there was a significant burn by glyphosate interaction. The burn was more thorough on the glyphosate plots. The investigator suggested that burning may be more effective if more fuel is present.

Mixed-grass prairie responses to spring, summer, and fall burning were measured in Nebraska (Wendtland 1993). The results of this study support the contention that fire can influence the production of smooth brome. All seasons of burning reduced the production of smooth brome (average 40%). Overall, it appears that smooth brome is most sensitive to summer burning. Annual prescription burns during the summer and possibly the fall might be the most effective fire treatments in reducing smooth brome.

Mixed-grass prairie in central North Dakota was burned on May 22 to study prescribed fire influence on bird habitat (Kirsch and Kruse 1973). Cover was measured in May two years after the burn. Smooth brome was reported as a decreaser while quackgrass and Kentucky bluegrass were reported as “no change” in this study.

Aspen (*Populus tremuloides*) parkland in east-central Alberta was burned annually in April for at least 24 years (Anderson and Bailey 1980). The native cool-season bunchgrass rough fescue (*Festuca scabrella*) was the dominant herbaceous species and smooth brome was a minor component. The 0.2% canopy cover of smooth brome in the burned-area transects was significantly ($p<0.01$) less than the 1.2% canopy cover in the unburned-area transects. However, the annual fires halved rough fescue cover from 36% to 18% ($p<0.005$). Others (Antos et al. 1983; Redmann et al. 1993) have measured decreased production of rough fescue after burning.

A factorial design was used to assess the response to prescribed burning and atrazine treatments of 11 heavily grazed pastures in southern Iowa (Rosburg and

Glenn-Lewin 1992). The investigators were interested in conversion of these pastures dominated by exotic cool-season grasses to native warm-season grass pasture. Exclosures were built, baseline community measurements made, and treatments to small plots initiated in the following year. Backing fires were used to burn the plots between late March and mid-April in a single year or twice with an intervening no-treatment year. Atrazine at 1.0 lbs/ac (2.2 kg a.i./ha) was applied approximately a week after the burn dates. Most of the cool-season perennial grass species decreased in response to the atrazine. The burning generally did not decrease the exotic cool-season grasses except in a drought year, nor did the fires benefit the warm-season perennial grasses. The investigators suggested several reasons why they did not obtain the benefits of burning demonstrated by so many other trials. Heavy grazing prior to exclosure construction had prevented heavy thatch build-up. The March burn in the first year of treatments was too early to cause direct injury to the cool-season grasses. Most of the studies reporting favorable responses have been conducted in prairie settings where the warm-season natives were still a major component of the system as well as having a heavy thatch layer. Remnant natives were sparse and patchy in these pastures and believed to be essentially absent from the seedbank.

Treatments of spring burning only, spring burns followed by glyphosate herbicide then drill-seeding warm season grasses, or spring burning followed by imazapic (Plateau®) herbicide then drill-seeding warm-season grasses were tested on 10 Kentucky sites with monotypic stands of the exotic cool-season tall fescue (*Festuca arundinacea*) (Washburn et al. 1999). The burning was done from March 7 to April 3 using strip head fires. The herbicides were applied one to two months later when the 6- to 8-inch (15- to 20-cm)-high tall fescue was actively growing. Methylated seed oil and nitrogen fertilizer were included with imazapic spraying. The drill-seeding was done from mid- to late-May. The spring burn followed by Plateau® was the most effective treatment. In September, tall fescue cover was absent at seven sites and less than 10% at the other three. The 10-site average cover for spring-burn-only was 87.3% and 92.8% on the controls, but burn-only reductions on two sites (to 65% and 75%) were statistically significant. The spring burn and glyphosate treatment was also effective in reducing tall fescue to an average cover of 5.7%, but the seeded warm-season grasses failed to establish. Establishment was 26.6% cover on the spring burn plus Plateau® (12 fluid oz/ac or 0.21 kg a.i./ha) sites.

A sequence of fall or spring burning, spring glyphosate, drill-seeding warm-season grasses, then applying imazapic after seeded grass establishment was tried at three tall-fescue-dominated sites in Kentucky (Washburn et al. 2002). Burning did not improve the generally high level of tall fescue suppression obtained after the 2 lbs/ac (2.24 kg a.i./ha) glyphosate-alone treatment, and this first stage of herbicide control was significantly less in some treatments that incorporated a burn. The spring imazapic spraying at 12 fluid oz/ac Plateau® (0.21 kg a.i./ha) was done two or three growing seasons after the drill-seeding. Tall fescue suppression was complete or nearly complete in the growing season after this second-stage herbicide treatment except at one site where tall fescue had 26% cover on the fall burn/spring glyphosate plots. Re-infestation from untreated edges may have influenced the measured responses on some plots. Overall, incorporating the burning did not improve tall fescue control beyond that obtained by the typically recommended rates of the two herbicides. The burning also did not contribute a consistent or large improvement in the warm-season grass establishment, which was generally quite successful.

Spring burning, imazapic (Plateau®) herbicide, and burning plus herbicide, were tested for release of native warm-season grasses in a tall fescue (*Festuca arundinacea*)-dominated abandoned pasture in the Kentucky barrens ecosystem (Rhoades et al. 2002; Washburn et al. 2002). The burning was done in late March by setting initial backing fires, then a headfire. Dry grass fuels averaged 5,505 lbs/ac (6,170 kg/ha) with close to 100% litter coverage. The burn consumed 95 to 100% of the grass fuels, but none of the woody debris. Maximum air temperatures were 482 to 752°F (250 to 400°C) at 4 in (10 cm) and 302 to 572°F (150 to 300°C) at 15.7 in (40 cm). Soil temperatures increased 90 to 180°F (50 to 100°C), but only to a maximum depth of 0.5 in (1.2 cm). The herbicide at 10 fluid oz/ac of product (0.18 kg a.i./ha) was applied one month later when the tall fescue had began to resprout. In the first growing season after the treatments, tall fescue cover was 46% on the controls, 29% on burn only, 18% on herbicide only, and 8% on the combination treatment plots. Imazapic efficacy was reduced by high litter cover. Initial warm-season grass response was greatest on the combination treatment plots, but warm-season grass cover did not differ significantly between burn-only and control plots.

The exotic Lehmann lovegrass (*Eragrostis lehmanniana*) shows fire adaptation by increased germination from the seedbank after burning (Ruyle et al. 1988; Sumrall et al. 1991). However, Lehmann lovegrass stands in southeast Arizona Chihuahuan desert shrub were burned to remove the canopy and kill adult plants prior to seeding native warm-season perennial grasses (Biedenbender et al. 1995). An August burn-then-sow treatment allowed the best establishment of native green spangletop (*Leptochloa dubia*). Juvenile Lehmann lovegrass was also most abundant on these burn plots. The investigators suggest that a two-step process would be necessary to replace Lehmann lovegrass: first, burning to stimulate seedbank-depleting germination, then a follow-up herbicide treatment to kill juvenile and surviving adult Lehmann lovegrass plants prior to seeding the desired natives.

Common reed (*Phragmites australis*) comprised 91% of the biomass in a marsh along Lake Manitoba (Thompson and Shay 1989). Portions of the marsh were burned by headfires in August at peak growth, in October after dormancy was established, or in May before growth began. All three burn dates increased shoot density in the summer after the burns. Aboveground biomass of common reed declined on the summer burns, was unchanged by the fall burns, and was increased by the spring burning. The reduction by summer burning was from 5,567 lbs/ac (6,240 kg/ha) on the controls to 3,711 lbs/ac (4,160 kg/ha). Species richness and Shannon-Weaver diversity increased significantly with the summer burns, but not the fall nor spring timings. Common reed is not reduced by fire unless root-burn occurs, but this is unlikely because water or mud usually covers the rhizomes (Marks et al. 1993; Marks et al. 1994). Burning after spraying may promote germination and initial establishment of other species because of increased light penetration. Common reed (*Phragmites australis*)-dominated marshes in southeast Virginia were treated by spraying for two years, and spraying followed by dormant-season burning and then a second herbicide application (Clark 1998). Quantitative measurements of density and frequency were made for treated and control stands. Common reed abundance was significantly reduced in the spray-burn-spray stands, but not in the spray-only stands. The proceedings abstract does not include the data, nor does it specify what herbicide was used.

Attempts to use fire to control reed canarygrass (*Phalaris arundinacea*) have been reported as not successful (Henderson 1990) by some operational managers, but effective by others (Grese 1992). These reports do not include data. Bahia grass (*Paspalum notatum*) cover in a Florida wetland was reduced 25% to 11% by burning prior to reflooding the site.

Exotic-dominated pasture plots in Great Smoky National Park (Tennessee and North Carolina) were subjected to a sequence of treatments to promote native species dominance (Price and Weltzin 2003). The dominant exotics were meadow rye grass (*Lolium pratense*), timothy (*Phleum pratense*), sericea lespedeza (*Lespedeza cuneata*), buckhorn plantain (*Plantago lanceolata*), and clovers (*Trifolium* spp.). The plots were mowed in late October, then glyphosate was applied while remnant warm-season native grasses were dormant but the cool-season grasses were still growing. Native forbs were drill-seeded the next spring. The plots were burned for four years in early spring. Meadow ryegrass was lower than controls for the first two years, but after four years its abundance in treated and control plots was similar. Buckhorn plantain and the clover declined about one-third relative to the controls. The natural vegetation of the site would be a closed-canopy deciduous forest.

Perennial Forbs

Leafy spurge (*Euphorbia esula*) plots in Minnesota were treated with various rates of herbicides followed by burning along with a burn-only treatment (Biesboer and Koukkari 1990). The plots were burned again in the second fall. The investigators were hoping to reduce herbicide usage. Burning alone was the least effective treatment. The highest herbicide rate (picloram at 0.25 lbs/ac + 2,4-D 1.0 lbs/ac) plus burning gave the best control, but there were no treatments of herbicide alone. The abstract did not include the data. Fall burn only, fall burn then two spring herbicide treatments, and spring herbicide-only treatments were made to leafy spurge plots in North Dakota (Prosser et al. 1999). The burn was done in October 1994 and the spraying in spring 1995 and 1996. The burning alone did not affect leafy spurge stem density. The herbicide spraying was at a normally recommended combination rate of 0.25 lbs/ac picloram plus 1.0 lbs/ac 2,4-D (0.28 kg/ha picloram plus 1.1 kg/ha 2,4-D) and a heavy rate where the picloram was double normal. The combination of burn plus normal herbicide rate gave better leafy spurge suppression than the normal spraying rate alone.

Herbicide alone, burning alone, and combination treatments were applied to leafy-spurge-infested prairie plots in southwestern North Dakota (Wolters et al. 1994). Spray or burn applications had fall timings and some were in spring. Leafy spurge seeds were separated from soil samples that included the mulch layer. Laboratory trials indicated significantly lower germination from treatments that included a burn. Maximum germination, which occurred with the controls, was less than 5%, rather low for leafy spurge. Burning alone did not reduce the leafy spurge density nor did its combination with spraying increase suppression beyond that obtained by herbicides alone. A standard recommended rate [picloram at 0.25 lbs/ac + 2,4-D 1.0 lbs/ac (0.28

kg/ha picloram + 1.1 kg/ha 2,4-D)] was used. The investigators concluded that a fall herbicide application followed by a spring burn would be the most effective treatment. This suggestion discounts the relative importance of vegetative reproduction by leafy spurge.

Frequencies of various species were measured in paired burned and unburned stands three years after a September wildfire in a western North Dakota grassland (Dix 1960). Leafy spurge frequency was 17% in the unburned stand and absent in the burned stand, but this probably was a pre-existing site difference as this retrospective study did not have pre-burn data. A North Dakota study designed to examine the interaction of prescribed fire and a leafy spurge biocontrol flea beetle (*Aphthona nigriscutis*) showed very large increases in leafy spurge stem density in the growing season following the burns (Fellows and Newton 1999). The burns were done in mid-October when the leafy spurge was dormant and mid-May when it was actively growing at 3 to 12 in (8 to 30 cm) high. Ninety-five to 100% of the standing vegetation and litter were removed at both burn timings. The increase in stem density was not significant in the second growing season after burning.

Spotted knapweed (*Centaurea biebersteinii*)-infested grassland plots in western Montana were subjected to a backing fire in April to remove litter (Carpenter 1986). In May these burn plots were sprayed with picloram (Tordon®), clopyralid (Transline®), and metsulfuron methyl (Escort®) herbicides at rates that were a fraction of the standard recommended rates for controlling spotted knapweed. Including burning with spraying did not improve knapweed control over that obtained by the same fractional rate of herbicide without burning.

A simulated burn was conducted for spotted knapweed seeds and seedlings in clay pots in a greenhouse (MacDonald et al. 2001). Three phenological stages were tested – pre-germination, cotyledon (1 week), and primary leaves (2 weeks) – and three fuel loadings – low, high, and a no-burn control. Dried grass clippings were used as fuel. Germination and seedling survival were measured until seedling densities stabilized. Seedling establishment was significantly reduced by burning at all three phenological stages including pre-germination. Timing, rather than fuel load, had a significantly greater effect on seedling establishment, with the greatest reduction caused by burning at the primary leaf stage. Reduced seedling establishment after the pre-germination burn was directly related to reduced germination, while lower seedling establishment after burning at the cotyledon and primary leaf stages was caused by the death of the burned seedlings. Seedlings that established after the cotyledon and primary leaf stage burns were almost entirely the result of post-fire germination rather than survival of burned seedlings. Seed germination in this experiment was higher than in the muffle furnace test done by Abella and MacDonald (2000), suggesting that the pot temperatures reached were lower than expected in an actual grassland fire with higher fuel loadings. The authors suggest that spring (April to early May) prescribed burns timed to kill recently emerged knapweed seedlings would be effective in reducing seedling recruitment. However knapweed seed germination is not synchronous even in laboratory plot trials. They also speculate that charred organic material might suppress allelopathic effects of spotted knapweed. This technique would be most effective for restoring communities in which warm-season grass species are stimulated by burning. Spring burns would injure many western bunchgrass species (Antos et al. 1983; Redmann et al. 1993; Weddell 2001; Wright and Klemmedson 1965).

A spotted-knapweed-infested prairie site in Michigan was burned in spring, summer, or fall on an annual or biennial schedule for four years (Emery and Gross 2003). The spring and fall burns did not affect the spotted knapweed. The annual summer burns reduced total production and fall seedling establishment. The biennial summer burns only reduced fall seedlings in the year of the burn and the knapweed population recovered in the no-burn year. The data are not included with the abstract. The investigators suggested that annual summer burning may potentially control spotted knapweed if the burning could be sustained long enough.

It has been reported that prescribed burning showed some promise to reduce diffuse knapweed (*Centaurea diffusa*) seed viability because the seeds are retained in the flowerhead for a long period while spotted knapweed seeds are released soon after they ripen (Renney and Hughes 1969). No data were presented.

In a review (Sheley et al. 1998) of spotted and diffuse knapweed it is stated: “A single low-intensity fire increased the cover and density of both weeds in northern Washington without altering the residual, desirable understory species.” A citation is given to an abstract of a control study using various treatments (Sheley and Roché 1982), however, the abstract does not present any data, does not directly discuss response to prescribed burning, and simply states: “Treatments which did not include a herbicide generally yielded the greatest amount of weeds and least amount of forage.”

Fall-applied picloram (0.25 to 0.5 lbs/ac or 0.28 to 0.56 kg/ha) plus 2,4-D (0.5 lbs/ac or 0.56 kg/ha) was reported as 98 to 100% effective in suppressing squarrose knapweed (*Centaurea triumfettii*) in Utah 32 months after spraying on a site that had burned in an August wildfire, but control in unburned areas was only 7 to 20% (Dewey et al. 2000). Investigators also reported a second study where fall-applied herbicides were more effective in wildfire areas than nonburned plots. Spring-applied herbicides did not perform better in wildfire areas. The abstract does not include the data nor study designs.

The Nature Conservancy manager reports give highly varied responses of Canada thistle (*Circium arvense*) to prescribed burning (Rice and Randall 2001). These reports usually do not include actual data on response nor descriptions of the burns. A report from an Illinois manager suggests that annual spring burns (May – June) control Canada thistle, but early spring burning promotes sprouting (Hutchison 1992). This report does not contain any data. Mixed-grass prairie in central North Dakota was burned on May 22 to study prescribed fire influence on bird habitat (Kirsch and Kruse 1973). Cover was measured in May two years after the burn. Canada thistle was reported as a decreaser (-50% or more) in this study. Canada thistle canopy cover in an Alberta wetland was not changed by using propane torches to simulate spring burns of low and high severity (Hogenbirk and Wein 1991). A mesic tallgrass prairie in a Colorado bottomland was infested with Canada thistle (Morghan et al. 2000). Small plots were burned in the spring five times over a seven-year period. The Canada thistle density was reduced by these repeated spring burns, but the investigators suggested that although frequently burned plots may be more resistant to invasion, repeat burning alone may not be enough to control this weed. Canada thistle density increased rapidly in a surrounding area after burning once. Canada thistle density increased 160% in the fall immediately following a summer burn directed at common reed in a Lake Manitoba marsh (Thompson and Shay 1989). Summer- and fall-burned common reed stands had significantly greater densities and biomass of Canada thistle stands than controls. Smaller increases in spring-burned stands were not significant. These increases in Canada thistle may be attributable to burn consumption of common reed thatch, increased light, and stimulated new bud formation. A post-wildfire recovery study in Yellowstone Park showed that Canada thistle increased with fire intensities in these coniferous habitats that burned in summer and fall (Turner et al. 1997). Canada thistle is a frequent invader of slash pile burns in conifer forests (Masters et al. 1992).

Mid-March burns were conducted in Montana big sagebrush/bluebunch wheatgrass (*Artemisia tridentata/Agropyron spicatum*) habitat types that were infested with Dalmatian toadflax (*Linaria dalmatica*) (Jacobs and Sheley 2003a). The burns were intended to improve wildlife habitat by reducing woody species including encroaching conifers. Flame lengths were 3 to 5 ft (1 to 1.5 m) and rates of spread were only 0.05 to 0.06 ac/hr (200 to 250 m^2/hr). Dalmatian toadflax response was measured in the fall after these late-winter burns. The fires did not affect density nor cover of toadflax, but seed production and biomass per plant was increased as well as biomass per unit area. A factorial experiment using spring burning, two herbicides (chlorsulfuron and picloram) applied the fall before burning and two weeks after the burns was conducted in the same habitat type (Jacobs and Sheley 2003b). Responses were measured in late summer of the treatments. The burns doubled the biomass and cover of the Dalmatian toadflax. All herbicides reduced toadflax to 90% of the control, so if there was a first-year interaction of fire with the herbicide treatments, it may have been masked by the high suppression obtained by the herbicides alone.

Experimental plots on Santa Cruz Island, California, annual grasslands containing fennel (*Foeniculum vulgare*) were treated by burning and/or spraying with triclopyr (Klinger and Brenton 2000). Burning alone did not reduce the fennel. Fennel cover was drastically reduced in the plots that were just sprayed. The burn-spray combination treatment virtually eliminated the fennel and there was a significant increase in the cover and number of native species. The investigators concluded that the burning enhanced the effectiveness of the herbicide. The abstract does not include treatment specifics nor the response data.

Burning and herbicide treatments of sulfur cinquefoil (*Potentilla recta*) were studied using a small-plot complete factorial design in a northwest Montana rough fescue (*Festuca scabrella*) grassland (Lesica and Martin 2003). Picloram (0.25 lbs/ac or 0.28 kg/ha) was applied in June and burns were done the following fall (October) and the next spring (April). The density of small sulfur cinquefoil plants on burn plots increased in the first year after the burns. Under the drought conditions that prevailed during the study, this did not lead to a sustained increase in population growth of the weed. The herbicide was highly effective, but sulfur cinquefoil seedling density after five years was higher in sprayed plots that also had been burned. The authors suggested that thermal decomposition reduced the soil residual of the herbicide. However, this is unlikely with a bunchgrass community burn as the decomposition point for picloram is 419°F (215°C) (Vencill 2002).

Spring burning at two- to three-year intervals did not restrict the spread of daylily (*Hemerocallis fulva*) in a tallgrass prairie remnant in Illinois (Solecki and Taft 1989). The daylily colonies did not have enough litter to carry the fires.

Repeat spring burning killed 96% of the absinth wormwood (*Artemisia absinthium*) plants in a South Dakota mixed-grass prairie (Steuter 1988). The perennating buds are at or near the soil surface. Burning was done in early May in four years over a five-year period. Senescent fine fuels in this habitat are 1,784 to 2,141 lbs/ac (2,000 to 2,400 kg/ha). Early green-up in some years can reduce intensity of early May burns. Summer (August) headfires of moderate intensity were also effective in killing absinth wormwood, but this timing had negative impacts on many native species (Steuter 1981).

Illinois vegetation management guidelines suggest that late spring prescribed burning can be used to control heavy infestations of trailing crown vetch (*Coronilla varia*) in the fire-adapted communities where it is invasive (Heim 1990). Several years of burning may be necessary. Data to support the recommendation are not given.

Woody Species

French broom (*Genista monspessulana*) and Scotch broom (*Cytisus scoparius*) have persistent seed banks, so management strategies need to consider depleting these reserves with a long-term burning program (Swezy and Odion 1998). Burning can kill some seed and stimulate germination by seedcoat scarification. Artificial heating of Scotch broom (*Cytisus scoparius*) seeds in soil to 149 and 212°F (65 and 100°C) for 60 seconds stimulated germination, and temperatures of 302°F (150°C) for 60 seconds made most seeds nonviable (Bossard 1993), suggesting to the author that prescribed burns could be used to flush germination and thus deplete the seedbank. The intermediate heating range increased susceptibility of emerging seedlings to fungal pathogens. The same author later reported that on a California Sierra Nevada foothills site, spring burning of dried Scotch broom cut the preceding fall killed the resprouts, killed the seed near the surface, and stimulated germination of deeper seed (Bossard 2000a). The spring post-burn seedlings then died in the summer drought. Overall reduction of the soil seedbank was 97%. At a wetter site in the Redwood National Park (California), the same treatment sequence only reduced the seedbank 52% and considerable follow-up treatment was required. Scotch broom seeds were added to small plots before and after burning (Parker 2001). Subsequent emergence of broom seedlings was higher on the plot where the seeds were added before burning, indicating that the fire promoted germination.

Small plots of young and old French broom stands in central California were burned twice in October to study the seed bank response (Odion and Haubensak 1997). It was necessary to cut the broom and leave the slash dry before it would carry an effective but controllable fire. The fuel on some plots was increased fourfold by addition of broom slash from adjacent areas. The young slashed stands had flame lengths of 1.6 to 5 ft (0.5 to 1.5 m) and 90 to 100% light ground char. Fuel-added young stands had 10- to 13-ft (3- to 4-m) flame lengths, longer residence (4 to 5 minutes) of flaming combustion, and 100% moderate ground char. The old broom slash plots had 1.6- to 8-ft (0.5- to 2.5-m) flame lengths, 2- to 4-minute residence times, and resulted in 80% moderate ground char and 20% deep ground char. In the old stand fuel-added plots, there was 4 to 6 minutes of flaming combustion, smoldering combustion continued long after, and deep ground char resulted. Second-year October burns had only limited fuels from sparse grasses and new broom seedlings. These second-year fires left 90% of the soil surface unburned. All of the first-year fires resulted in high densities of French broom seedlings and promoted spread into adjacent grasslands, confirming the need for repeat burning. The fuel additions to the old stands did not increase seed bank depletion and had a negative effect on reestablishing native plant cover. However, the investigators suggested that fuel additions to young stands might deplete the seed bank more rapidly. A retrospective seedbank survey was conducted of different-age French-broom-infested coastal grasslands in northern California where fire was being used to suppress the broom (Alexander and D'Antonio 2003). There was a very large decrease in the French broom seedbanks after burning once. However, repeat burning of the stands as often as four times, with one- to two-year periods between burns, did not reduce seedbanks significantly more than burning one time. Sampling before and immediately after the burn did not show a significant reduction in the seedbank nor an increase in dead seeds. These immediate post-burn sampling results confirmed that benefit of burning was increased germination rather than mortality of broom seeds. There was no apparent relationship between stand age and the size of the seed bank, suggesting that the seed bank stayed constant or declined slightly with stand age, so prescribed burning would be equally effective regardless of stand age.

Scotch broom thickets in western Washington fescue prairie and oak woodland sites were burned in fall (September) or early spring (March) (Tveten and Fonda 1999). The areas under thick broom canopies where grass was lacking and fuel moisture high did not burn well. Flame lengths were less than 6.6 ft (2 m) in these low-intensity fires that only reduced fuel loads from 2,502 lbs/ac to 1,648 lbs/ac (2,804 kg/ha to 1,847 kg/ha) for the fall burns. Higher temperatures were measured in the fall burns, more area was burned, broom mortality was higher, and basal resprouting less. Cover was reduced from 62.8% before the fall burn to 1.9% in the summer after, but frequency of occurrence (10.7 ft^2 or 1 m^2 microplots) was still 96% so repeat burning would be necessary. The patchy spring burn reduced seedling density but had no other significant effects.

French broom canopy cover in California was reduced from 87% to less than 0.2% by applying triclopyr herbicide (Garlon®), cutting, burning, then treating the new broom seedlings with glyphosate (Bossard 2000b). A basal bark application of triclopyr (Garlon®) with a methylated seed oil adjuvant was made in July. A month later the dead broom was cut and the site burned. The next rains induced a germination flush. Glyphosate was used to spot-spray the broom seedlings in July for two years after the burn. A brushcutter rather than glyphosate was used to destroy the seedlings in some plots. Broom density was reduced to 6,475 resprouts/ac (1.6 resprouts/m^2) in the brushcutter plots and 809 resprouts/ac (0.2 resprouts/m^2) in the plots with the glyphosate follow-up. French broom was cut and allowed to dry at another site in California (Boyd 1996). The resultant cut fuel bed was 2 to 3 ft (0.6 to 0.9 m) deep. Fine fuels were lacking but the dry cut broom and slope allowed an intense headfire in May. The burn killed the mature French broom and prevented resprouting. Rainfall occurred shortly after the burn and a French broom seed germination flush survived the summer drought. In late November, two exotic annual grasses [soft brome (*Bromus hordeaceus*) and rattail fescue (*Vulpia myuros*)] were broadcast-seeded into the broom seedlings in an attempt to create continuous fine fuels. An earlier seeding of grain barley (*Hordeum vulgare*) had failed to establish. Late the following July, after the seeded annual grasses had dried, the site was burned for a second time to kill the broom seedlings. An initial measurement seven weeks after the second burn indicated that only 0.4% of the broom seedlings were resprouting. A second burn-response measurement after the normal fall germination period would be necessary to evaluate the longer-term benefit of this integrated control strategy.

Managers of fire-adapted Midwest plant communities often suggest that annual or biennial repeat burning is effective in controlling buckthorns if the treatment can be maintained for five or six years (Grese 1992; Heidorn 1991). European buckthorn (*Rhamnus cathartica*) and smooth buckthorn (*Frangula alnus*) were reported to decline in an Illinois mesic oak savanna after prescribed burning of some kind, and to increase in the absence of fire in other oak savannas (Haney and Apfelbaum 1990). Mid-April burns for two years reduced European buckthorn and honeysuckle (*Lonicera* x *bella*) in a southern Wisconsin oak forest (Kline and McClintock 1994). The April fires were of low intensity with flame lengths of 6 to 12 in (15 to 30 cm) burning 50 to 70% of the area. The cover of buckthorn and honeysuckle was 85% in the year before the first burn, 56% in the year after the first burn, and 38% after the second burn. The woody exotic cover increased slightly to 41% in the third year, but the resprouts were not very vigorous. Herbaceous ground layer species, including exotics, increased after each burn in this study, probably because of the reduction in shading by overstory. Propane torch flaming was used to girdle the cut stumps of European buckthorn in Saskatchewan with the intent of suppressing resprouting (Archibold et al. 1997). The flaming was for two to three minutes at 1,832°F (1,000°C), more severe than the 932 to 1,292°F (500 to 700°C) 20- to 30-second maximum typical of shrub fires in this area. This single-event simulated fire was ineffective. Personnel at a Minnesota riparian wood and oak savanna preserve monitored European buckthorn response to mid-April through mid-May burning (Boudreau and Willson 1992). They observed that fire could top-kill mature trees but resprouting occurs. Seedlings were susceptible to fire-induced mortality, but the seedlings were most often establishing in areas with insufficient fuel. A smooth buckthorn plot in a dry sand prairie in northwest Indiana was burned twice (Post and McCloskey 1990), first in October 1986, then in April 1988. The stems were top-killed by both fires but the number of stems increased 48% after the first burn and 59% after the second burn.

Vegetation management guidelines suggest that spring prescribed burning can be used in fire-adapted communities to kill seedlings of bush honeysuckles (*Lonicera* spp.) and top-kill mature plants, but annual or biennial burns for five or more years are necessary for adequate control (Nyboer 1990). Data were not presented to support this recommendation nor burn prescriptions. These species can invade wetlands, prairies, and forests.

The Nature Conservancy managers in Alabama reported that prescribed burning top-kills European privet (*Ligustrum vulgare*) and Chinese privet (*Ligustrum sinense*) and eliminates them over time, and that burning controls Chinese privet if done annually under droughty conditions (Batcher 2000). No data were presented.

Broadcast prescribed burning or pile burning is often incorporated in the management of saltcedar (*Tamarix* spp.), usually in conjunction with other treatments (Taylor and McDaniel 1998). Burning is sometimes used to reduce initial stand density and prepare for other types of treatments (Racher and Britton 2003). Direct fire mortality in stands along the Pecos River in New Mexico has averaged 30%. A burn-only treatment opens dense canopies for herbaceous forage supporting wildlife and livestock. This saltcedar stand-thinning by broadcast burning is a long-established practice, but there is resprouting from many of the burnt stumps (Turner 1974). Burning can be used as an initial treatment followed by mechanical or herbicide treatments. Fire can be used after herbicide spraying to remove excessive biomass that interferes with restoration work and to kill post-spray new saltcedar plants while they are still susceptible to burning. Integration of burning with the other treatment methods can lower overall cost of saltcedar suppression. Extensive research on saltcedar fire behavior and integrating burning with other methods is being conducted in Texas and New Mexico (Racher and Mitchell 1999; Racher et al. 2001). Saltcedar (*Tamarix ramosissima*) and athel tamarisk (*Tamarix aphylla*) infesting very arid sites in southern California were cut and the debris piled around the stumps (Coffey 1990). The intense pile-burning caused complete mortality of the cut stumps and roots. Stump-root burning was not attempted on sites that still had water.

The National Park Service has been using prescribed burning for over a decade as part of their saltcedar suppression efforts in the Lake Mead (Nevada and Arizona) area (C. Deuser, personal communication). The burn objective is to implement crown fires that will consume as much aboveground biomass as possible. Early fall (September-October) timing is typical to avoid killing nesting birds but still have temperature and humidity conditions that allow crown fires. Summer burns would be more effective if birds are not a consideration. It is also beneficial to consume the saltcedar ground litter that inhibits desirable plant establishment. Sustaining heat at ground level is necessary to maximize root crown injury. Direct mortality in these fires is 10% or less. Resprouts are treated with low-volume basal sprays within six to 12 months following the burn. The post-burn herbicide treatment increases mortality to >95%.

Some managers believe fire could be used to stop Brazilian pepper (*Schinus terebinthifolius*) trees from invading fire-adapted wetlands (Wade 1988). The interaction of fine fuel amounts and size of Brazilian pepper trees was studied in the southern Florida Everglades (Doren and Whiteaker 1990). There was less fuel under the canopy of bigger Brazilian pepper trees. The larger trees were not injured or recovered rapidly from the less severe burns. More recently established smaller saplings were killed or severely retarded by initial burns when fuel loads were high under their canopies, but overall, even repeat burning would not prevent invasion. The number and density of Brazilian pepper stems increased in spite of burning every year or two, depending on fuel availability, over six years using backing fires during the spring dry season (Doren et al. 1991).

Even though melaleuca (*Melaleuca quinquenervia*) is fire-adapted, prescribed burning of fire-promoted seasonal wetlands in Florida two to 12 months after a herbicide treatment can kill seedlings and small saplings (Molnar et al. 1991; Myers et al. 2001; Timmer and Teague 1991).

Wetland prairie in the Willamette Valley of Oregon has been invaded by native and exotic woody species as a consequence of fire suppression (Pendergrass et al. 1988). The major woody exotics were sweetbriar rose (*Rosa eglanteria*), Himalayan blackberry (*Rubus discolor*), cutleaf blackberry (*Rubus laciniata*), English hawthorne (*Crataegus monogyna*), and common pear (*Pyrus communis*). Sites were burned between mid-September and mid-October once or in two consecutive years. Flame lengths ranged from 3.6 to 7.2 ft (1.1 to 2.2 m) and residence times were 7 to 24 seconds. Other very detailed measurements were made of the fire behavior. The permitted low-intensity fires consumed smaller woody shoots but were not intense enough to kill belowground meristematic tissues of woody species. Common pear and the blackberries were among 14 woody exotics that increased after the burns, in part because of thatch removal. A second analysis of compositional shifts associated with initial reintroduction of burning to this wetland prairie also cautioned that fire was not significantly reducing the dominant exotic sweetbriar rose (Streatfeild and Frenkel 1997). Of mostly herbaceous species, 77% of the exotics were negatively correlated with recency of burning and number of burns. Cover of the exotics St. Johnswort (*Hypericum perforatum*), annual yellow glandweed (*Parentucellia viscosa*), and even Kentucky bluegrass increased with recency of burning in this wetland.

Winter dormant burning in Texas coastal tallgrass prairie was the best seasonal timing to reduce the topgrowth of the evergreen Macartney rose (*Rosa bracteata*) and improve herbaceous forage (Gordon and Scifres 1977). Total fuel loads in January were 5,767 lbs/ac (6,464 kg/ha). The headfires had flame lengths in excess of 26 ft (8 m), rates of spread exceeding 48 ft/min (14.5 m/min), and average maximum temperature of 639°F (337 °C) at ground line. Initial Macartney rose canopy reduction was 96%. However, cane resprouting started two weeks after burning, and reburning was necessary at two- to three-year intervals. New canes on burned sites were more prostrate and canopy heights were lower than on unburned sites because the old canes acted as trellises. Burning the canes facilitated access and management of livestock, and also allowed easy entry for ground application of herbicides. Winter-burning 18 months after fall aerial spraying of a mix of picloram and 2,4,5-T increased topgrowth control over that of spraying alone and provided acceptable control for three years (Scifres 1975). Fine fuel was 3,125 lbs/ac (3,503 kg/ha), not including the Macartney rose canes. Surface soils were saturated and had standing pools of water during the February burn. Fuel moisture was high, but the ambient conditions were clear, warm, and sunny with wind speeds of 12 to 15 mph (19.3 to 20.1 km/hr). Temperatures averaged 581°F (305°C) at the soil surface and 1,160°F (627°C) at 6 in (15 cm) high. Cane burn-down was in excess of 95% on the previously sprayed plots. However, burning did not improve control beyond that from picloram pellets without burning (Gordon et al. 1982).

Chinese tallow (*Sapium sebiferum*) is a fire-adapted tree, but prescribed burning when trees are small and of limited density may prevent its dominance of southern coastal prairies (Grace 1998; Grace et al. 2001). High fine fuel loads could kill even large trees if the burns can be repeated frequently. Growing-season burns appear to be more effective in suppressing basal resprouts than dormant-season fires. Research on using fire to suppress Chinese tallow is still at an early stage.

Single fires may temporarily reduce aboveground Japanese honeysuckle (*Lonicera japonica*), but this woody vine then resprouts from roots. Spring burning was tested for the suppression of Japanese honeysuckle in Illinois barrens (Anderson and Schwegman 1971). Barrens are transition zones between prairies and forests. The treatment area was first burned in mid-March, then burned again in early April of the following year. The first burn removed most of the Japanese honeysuckle vines from the overstory to heights of 10 to 15 ft (3 to 4.6 m), but frequency of occurrence was unchanged as the honeysuckle resprouted from rootstocks. The second burn was just after the buds on Japanese honeysuckle resprouts had opened, but the prairie species were still dormant. Frequency of occurrence was reduced from 24% to 12% after the second burn. Two successive low-intensity fall burns were conducted in a North Carolina pine-hardwood forest heavily infested with Japanese honeysuckle (Barden and Matthews 1980). These fires killed most of the aboveground vines. Crown volume of resprouts was reduced by 80% and cover by only 35%. Japanese honeysuckle was still the dominant groundcover after two burns. A third burn was done after a one-year period without burning (Barden 1982). Crown volume was reduced by 61% and cover by 49% after the final burn.

Biocontrol Agents and Fire

Fuel reduction burns were conducted the spring of 1982 and fall 1986 in a St. Johnswort-infested *Eucalyptus* forest in Australia (Briese 1996). The low-intensity burns increased crown density and flowering of St. Johnswort, particularly after the spring burn. Populations of the Klamath weed beetle (*Chrysolina quadrigemina*) crashed as a result of the prescribed burns. However, the biocontrol agent populations rebounded strongly because an influx of beetles from adjacent unburned areas thrived on the St. Johnswort which had nitrogen enrichment as a consequence of the burns. The investigator suggested that a mosaic of small-scale prescribed burns in big patches of the target weed could be used to build up populations of biocontrol agents. Briese also suggested that burning could be used to stimulate germination prior to application of host-specific mycoherbicides. Others have noted that intermediate heating of Scotch broom (*Cytisus scoparius*) seeds increased fungal mortality of post-burn germinates (Bossard 1993).

Leafy spurge plots in North Dakota were burned in mid-October and mid-May before the introduction of a leafy spurge flea beetle (*Aphthona nigriscutis*) (Fellows and Newton 1999). The leafy spurge was senesced for the fall burn but actively growing during the spring burn. Both burns consumed 95 to 100% of the standing vegetation and litter. Flea beetle establishment was more successful on the burned plots (87%) than the unburned plots (37%). There was a positive correspondence between bare ground and colonization. Plots where flea beetle colonies had established were then burned in mid-October or mid-May to determine whether the insect populations would be affected by fire after they had established. The adults were not active and juveniles were belowground at the time of both burns. The flea beetles were not affected by these post-establishment burns. The authors caution that spring burns of established colonies must be early enough to allow leafy spurge regrowth before adult beetles emerge. There was no reduction in leafy spurge density attributed to the flea beetles in this short-term small-plot study. However, monitoring of a large operational release showed greater leafy spurge suppression by flea beetles in the first year after release on an area that had been spring-burned prior to the beetle release than in the adjoining area that was not burned.

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