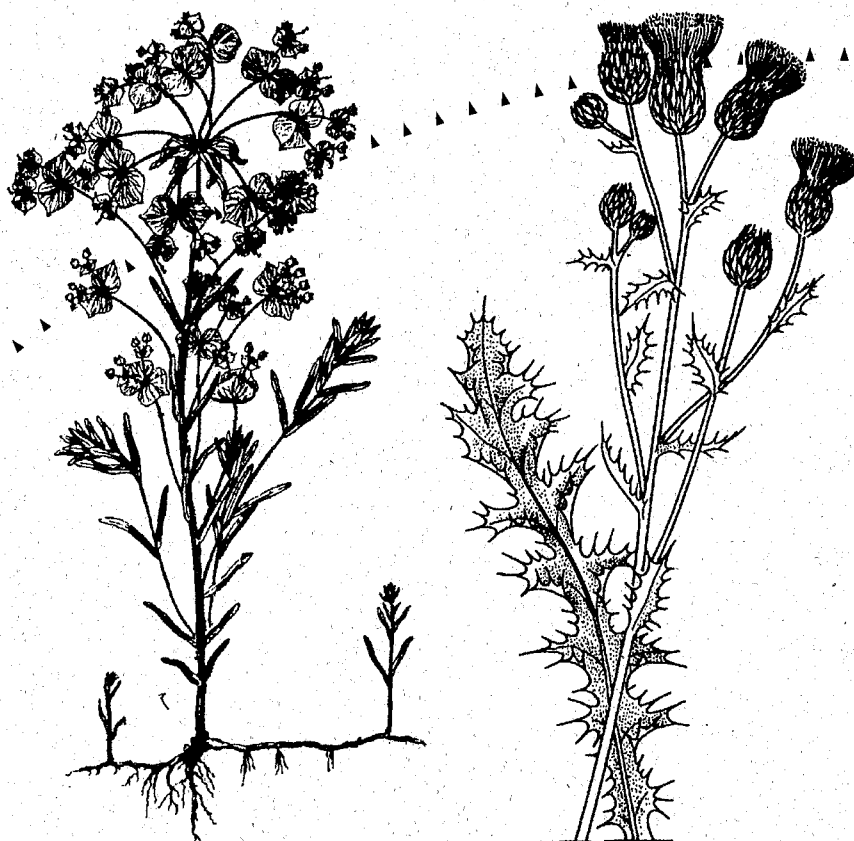




Controlling Leafy Spurge and Canada Thistle by Competitive Species

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CONTROLLING LEAFY SPURGE AND CANADA THISTLE BY COMPETITIVE SPECIES

Final Report

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Executive Summary

One purpose of the study was to evaluate the interfering ability of several perennial grasses with leafy spurge (*Euphorbia esula* L.) and Canada thistle (*Cirsium arvense* (L.) Scop.) using an integrated vegetation management approach. Grass interference was evaluated in the laboratory and in the field in southeastern Minnesota. Laboratory experiments consisted of grass and leafy spurge or Canada thistle seedlings grown together in pots. The effects of the grasses on root and shoot biomass of both leafy spurge and Canada thistle were determined. Of the five grass species tested, only the two cool-season grasses, Canada wildrye (*Elymus canadensis* L.) and smooth brome (*Bromus inermis* Leyss.), established well under the greenhouse growing conditions and significantly reduced the root biomass of both Canada thistle and leafy spurge. Field experiments were located in either leafy spurge or Canada thistle infested areas and consisted of plots seeded with various perennial grasses as monocultures and in combinations. Several management techniques, such as burning, mowing, fertilizing, and herbicide spraying, were used to promote grass establishment and reduce leafy spurge and Canada thistle. The effects of both the grass and herbicide treatments on the above-ground percent cover of leafy spurge or Canada thistle were evaluated. Results from the field experiments indicate a negative correlation between degree of grass establishment and leafy spurge cover. Three grass treatments, little bluestem (*Schizachyrium scoparium* (Michx.) Nash), little bluestem + side-oats grama (*Bouteloua curtipendula* (Michx.) Torr.), and little bluestem + side-oats grama + buffalograss (*Buchloe dactyloides* (Nutt.) Engelm.) established well and significantly reduced the cover of leafy spurge. The effects of the grasses could not be evaluated for Canada thistle in the field experiments due to poor grass establishment. The herbicide treatments picloram at 1.0 lb/acre and imazethapyr at 0.25 lb/acre both were very effective in controlling leafy spurge but only for about one year. For preparation of the site prior to seeding the grasses, glyphosate at 1.4 lbs ai/acre followed by disking was very effective at reducing leafy spurge cover prior to grass establishment.

A second purpose of the present study was to investigate the effects of a late season application of the herbicides picloram and glyphosate on the vegetative crown buds of leafy spurge. The phenology of leafy spurge crown buds was also studied to determine when the crown buds would potentially be most vulnerable to a herbicide application. Crown bud growth was found to be a gradual process beginning shortly after flowering in mid-June and obtaining maximum size during senescence in October. Both picloram (1.0 lb ai/acre) and glyphosate (1.0 lb ai/acre) applied to senescing leafy spurge in the field in October significantly inhibited shoot expansion when grown under favorable conditions in the laboratory. Picloram applied directly to crown buds of fall collected leafy spurge crowns significantly inhibited bud growth. An

experiment using ^{14}C -picloram applied directly to crown buds at a rate approximating a field application of 0.5 lb ai/acre, indicated that picloram could be directly absorbed by the buds and inhibit bud elongation. Although glyphosate applied directly to crown buds did not significantly reduce bud elongation, the data does suggest that some glyphosate absorption had occurred. The long term effects of a fall application of picloram at 0.5 and 1.0 lb ai/acre resulted in significant reductions in leafy spurge above-ground cover in the two years following treatment. Glyphosate applied in the fall at 1.0 lb ai/acre resulted in a significant increase in leafy spurge above-ground cover by the following summer. Burning in the spring subsequent to the fall herbicide applications did not increase leafy spurge control. A late season application of picloram is thus more effective than glyphosate at controlling leafy spurge due to its ability to persist in soil and directly target the crown buds.

Based on the findings of the present study, the use of native prairie grasses as part of an integrated vegetation management program is a feasible approach to the control of leafy spurge and Canada thistle along Minnesota roadside right-of-ways. The use of native prairie grasses would also provide many other benefits in addition to weed control. The choice of native grass species to use would depend on the specific conditions present at each site. Herbicides would still be needed but at reduced rates. The herbicide picloram applied in the fall at 0.5 and 1.0 lb ai/acre was very effective at targeting leafy spurge crown buds and providing long-term control.

Introduction

Leafy spurge and Canada thistle are noxious deep-rooted perennial weeds that require control along highway right-of-ways. Traditional management of these weeds has relied heavily upon the usage of high rates of herbicides which are costly, environmentally unfriendly, and represent only a short term solution to the problem. A new long term approach to weed control is that of integrated vegetation management which uses combinations of weed control methods applied at the most appropriate times and in the most appropriate ways to maximize injury to the weeds and encourage the growth of the desirable species. An integrated vegetation management approach thus requires a thorough understanding of the biology and ecology of the weed so that weed control practices can be applied most efficiently.

The Minnesota Department of Transportation (Mn/DOT) has recently begun seeding native species in the roadside rights-of-way because introduced species, such as brome and Kentucky bluegrass which had been planted extensively along the roadsides, deteriorate over time and allow the establishment of weeds. The use of native vegetation along roadsides has many advantages, one of which is the potential to better compete with the invading weeds. One of the main purposes of the present study was to evaluate the ability of several native prairie grasses to compete with leafy spurge and Canada thistle (Chapter 2). A second purpose was to determine how to best target the vegetative buds of leafy spurge in our control practices (Chapter 3). Lastly, the third purpose of the study was to make recommendations to Mn/DOT in their management of leafy spurge and Canada thistle infestations along roadside rights-of-way. (Chapter 4).

Chapter 1. Introduction

Leafy Spurge

Leafy spurge (*Euphorbia esula* L.) is a deep-rooted perennial weed which has become a serious problem in the Great Plains region of the United States and Canada (Pemberton 1985). In North America, leafy spurge is actually a complex of forms, species, and hybrids (Pemberton 1985, Dunn and Radcliffe-Smith 1980), the taxonomy of which is still unresolved. Leafy spurge has likely been introduced many times into North America from different regions of its native range in Eurasia (Best *et al.* 1980, Dunn and Radcliffe-Smith 1980). As early as 1827, leafy spurge was present in Massachusetts (Britton 1921). Most likely leafy spurge was introduced to North America as contaminants in ship ballast brought from Eurasia (Galitz 1980). It is thought that leafy spurge was introduced into southwestern Minnesota as a contaminant in oats brought from southern Russia in 1890 (Batho 1932 as cited in Bakke 1936). Although leafy spurge is adapted to a wide range of conditions, it is most commonly found and more vigorous in soils of coarse texture (Selleck *et al.* 1962). It occurs most often in grasslands and waste areas at sites which are not subject to frequent cultivation (Morrow 1979).

Leafy spurge reproduces both by seed and vegetatively. Like other members of Euphorbiaceae, the unisexual flowers are born in a cup-like structure called a cyathium (Raju 1985). The cyathia are arranged in terminal umbellate inflorescences on the shoot (Raju 1985). Insects are the principal pollinating agents (Bakke 1936, Selleck *et al.* 1962). The mature capsules, each containing three seeds, dehisces explosively disseminating the seeds as much as 15 feet away from the plant (Bakke 1936). Average seed yield has been found to be as high as 252 seeds per shoot (Selleck *et al.* 1962). The seeds can float on water and germinate readily (Bakke 1936). Leafy spurge reproduces vegetatively by buds located on the vertical underground portion of the shoot (the crown) and on the roots. Leafy spurge thus occurs in patches which can coalesce to form large stands (Pemberton 1985). The expansion of a patch is mostly the result of lateral long roots spreading out from the parent plant (Best *et al.* 1980). The perimeter of a patch usually extends from 2 to 3 ft in all directions in one season, although extensions greater than this have been documented (Selleck *et al.* 1962). The root system is very deep and extensive (Bakke 1936, Coupland and Alex 1954). Roots containing vegetative buds are predominantly present near the soil surface but can be found at much greater depths (Coupland and Alex 1955). Upon disturbance, root fragments from considerable depths have the capacity to initiate new buds and subsequently produce shoots (Raju *et al.* 1964).

The persistence of leafy spurge can be attributed to its deep and extensive root system which has an unlimited ability for regeneration; the presence of cork on the roots which forms a

protective covering that resists drying (Bakashi and Coupland 1959); an efficient starch storage system in the roots (Bakke 1936, Bakshi and Coupland 1959, Dunn 1979); few natural enemies (Dunn 1979); and, a large long-lived soil seed bank present for reestablishment (Bowes and Thomas 1978).

Canada Thistle

Canada thistle (*Cirsium arvense* (L.) Scop.) is a naturalized perennial weed found throughout the northern half of the United States (Hodgson 1968), most commonly in agricultural areas (Moore 1975). Canada thistle probably was originally native to southeastern Europe and the eastern Mediterranean area but now occurs throughout Europe, North Africa, Asia Minor, across central Asia to Japan, South Africa, New Zealand, southeastern Australia, Canada, and the United States (Moore 1975). It most likely was introduced into North America as an impurity in crop seeds from Europe during the 17th century (Hodgson 1968, Moore 1975).

Canada thistle is found in open mesophytic areas in a wide variety of soils (Moore 1975). It can survive in dry habitats but does not do well in very wet soils (Moore 1975). The roots grow down to penetrate saturated soil so that the ultimate root length attained is determined by the depth of the water table (Hayden 1934). Seedlings require high levels of light for establishment thereby being successful only in disturbed soils where competition is limited (Hodgson 1968). Good light intensity is also required for flower production (Moore 1975).

Canada thistle reproduces vegetatively by an extensive underground root system and also sexually from seed. Canada thistle typically occurs in patches of genetically identical plants (Hodgson 1968). The radial growth of a patch can be rapid if competition is at a minimum (Hoefer 1981). Although the florets are perfect, Canada thistle is functionally dioecious (Hayden 1934). Staminate and pistillate patches must be within close proximity of each other for large quantities of seed to be produced (Hayden 1934, Hodgson 1968). Insects are the primary means of pollination (Derscheid and Schultz 1960). The plumose achene is dispersed by wind (Hayden 1934).

The persistence of Canada thistle despite great control efforts is largely due to its vigorous, horizontally spreading root system which can readily regenerate new shoots from adventitious buds located at any position along the roots (McAllister and Haderlie 1981). Adventitious root buds have the potential to produce new shoots at any time of the year after removal of the existing above-ground shoots (McAllister and Haderlie 1981). Fragments of Canada thistle roots only 10 mm long, even without the presence of visible buds, were able to produce shoots (Hamdoun 1972). Also, aerial and subterranean stem fragments left by tillage could form roots and produce new thistle infestations (Magnusson *et al.* 1987).

Long-term control of both leafy spurge and Canada thistle has been extremely difficult to achieve. In a limited number of situations, herbicides have been effective, but only for short durations. Herbicides are expensive and their use has become more restrictive, especially since they may contaminate ground water, persist in the soil, and must be applied continually to achieve even moderate control. A new approach to weed control practices, that of integrated vegetation management, shows great promise in managing populations of leafy spurge and Canada thistle.

Integrated Vegetation Management

Integrated vegetation management involves the use of combinations of weed control methods applied at the most appropriate times and in the most appropriate ways to maximize injury to the weed and promote the growth of the desirable species. Weed control methods presently available today include cultural (interfering plant species), physical (tilling, mowing, and burning), chemical (herbicides and fertilizing), and biological control (insects, pathogens, and grazing). The use of more than one method in the control of leafy spurge or Canada thistle at a particular site is not a new practice (e.g., see Derscheid *et al.* 1961, Derscheid *et al.* 1963, Hodgson 1958, and 1968, Selleck *et al.* 1962, and Thrasher *et al.* 1963). New management tools, such as biocontrol with insects and pathogens, are being developed and some are presently available for incorporation into an integrated weed control programs (Lym 1992). It is most important to apply the control method(s) such that the target plant is stressed but the desirable plant species are not injured and thus allowed to interfere with the weed (Beck 1992). As pointed out by Beck (1992) in the case of herbicide use, no single herbicide is ideally suited to use in every habitat for weed control. Herbicide use should be integrated into a management system where herbicide choice, rate, application timing, and frequency of application are tailored to the environmental situation (Beck 1992). This point should be extended to include any combination of weed control methods. In order to fine tune weed control practices to specific sites, basic information about the biology and ecology of the weeds as well as the desirable species are needed. This basic research could lead to the development of new weed control practices and to the improvement of already existing practices (Wyse 1991).

Objectives

The purposes of the present study were to: (1) evaluate the interfering ability of several perennial grasses established within leafy spurge and Canada thistle infestations along with an integration of additional vegetation management tools; (2) to investigate the effects of fall applied herbicides to the below-ground portions of leafy spurge; and (3) to make recommendations to the Minnesota Department of Transportation in their management of leafy

spurge and Canada thistle infestations along roadside right-of-ways. This study included the following objectives:

- (1) To determine which management practices are beneficial to the establishment of desirable perennial grasses within leafy spurge and Canada thistle infestations in Minnesota;
- (2) To determine which combinations of perennial grass specie(s) will reduce cover of leafy spurge in Minnesota;
- (3) To determine which combinations of perennial grass specie(s) will reduce cover of Canada thistle in Minnesota;
- (4) To determine which herbicide(s) can effectively reduce leafy spurge and Canada thistle cover without being detrimental to the desirable perennial grasses;
- (5) To determine when leafy spurge crown buds are most actively elongating so that weed control practices can be applied at the time when injury to these perennating organs is maximized;
- (6) To evaluate the effects of a late season herbicide application of picloram and glyphosate on the elongation of leafy spurge crown buds;
- (7) To determine if the herbicides picloram and glyphosate can be directly absorbed by leafy spurge crown buds and subsequently affect their elongation; and,
- (8) To evaluate the long-term effects of a late season herbicide application of picloram and glyphosate followed by a spring burn on leafy spurge above-ground cover.

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Chapter 2. Controlling Leafy Spurge and Canada Thistle with Competitive Species and Combined Management Practices.

Abstract

The interfering ability of several perennial grasses were evaluated in the laboratory and in the field as part of an integrated vegetation management program designed to control infestations of leafy spurge (*Euphorbia esula* L.) and Canada thistle (*Cirsium arvense* (L.) Scop.). Laboratory experiments consisted of grass and leafy spurge or Canada thistle seedlings grown together in pots. The effects of the grasses on the root and shoot dry weights of both leafy spurge and Canada thistle were determined. Of the five grass species tested, only the two cool-season grasses, Canada wildrye (*Elymus canadensis* L.) and smooth brome (*Bromus inermis* Leyss.), established well under the greenhouse growing conditions and significantly reduced the root dry weights of both Canada thistle and leafy spurge. Field experiments were located in either leafy spurge or Canada thistle infested areas and consisted of plots seeded with various perennial grasses as monocultures and in combinations. Several management techniques, such as burning, mowing, fertilizing, and herbicide spraying, were used to promote grass establishment and reduce leafy spurge and Canada thistle. The effects of both the grass and herbicide treatments on the above-ground percent cover of leafy spurge or Canada thistle were evaluated. Results from the field experiments indicate a negative correlation between degree of grass establishment and leafy spurge cover. Three grass treatments, little bluestem [*Schizachyrium scoparium* (Michx.) Nash], little bluestem + side-oats grama [*Bouteloua curtipendula* (Michx.) Torr.], and little bluestem + side-oats grama + buffalograss [*Buchloe dactyloides* (Nutt.) Engelm.] established well and significantly reduced the cover of leafy spurge. The effects of the grasses could not be evaluated for Canada thistle in the field experiments due to poor grass establishment. The herbicide treatments picloram at 1.0 lb ai/acre and imazethapyr at 0.25 lb/acre were very effective in controlling leafy spurge but only for about one year. For preparation of the site prior to seeding the grasses, glyphosate at 1.4 lbs ai/acre followed by disking was very effective at reducing leafy spurge cover during grass establishment.

Introduction

Plant interference can be broadly defined as the total influence of one plant upon another. This interference can be mediated via the removal of one or more limiting resources such as

light, nutrients, or water (competition), via the production of toxic chemical compounds that are released into the environment (allelopathy), and via indirect sources of interference such as harboring herbivores, carrying pathogens, and encouraging foraging birds and mammals (Harper 1977, Fuerst and Putnam 1983). The potential exists for usage of these plant interactions for weed control purposes. Competitive and allelopathic interactions in the control of weeds are well documented (Evetts and Burnside 1975, Putnam and Duke 1978, Putnam 1983, Putnam and DeFrank 1983, Duke 1986, Jobidon 1986, Burke 1987, Ku 1987).

Results from several studies have shown that leafy spurge and Canada thistle can be negatively influenced by neighboring species. Selleck (1972) observed small everlasting (*Atennaria microphylla*) to interfere with the growth of leafy spurge and the results of his experiments suggests this interference as being allelopathic. Further work has found the compound hydroquinone isolated from small everlasting to be involved in this allelopathic interaction (Manners and Galitz 1986, Manners 1987, Hogan and Manners 1990, and 1991). Preliminary experiments have shown sunn hemp (*Crotalaria juncea*) to have allelopathic potential against leafy spurge (Leather 1990). Best *et al.* (1980) monitored leafy spurge seedling establishment in artificially seeded plots on a native grassland habitat, cultivated crops, and a patch of wolfberry (*Symphoricarpos occidentalis*) and found that the % survival of seed sown was greatest in the cultivated plots and least in the native grassland habitat. Selleck *et al.* (1962) also found leafy spurge seedling density to be low in competition with native grasses in Saskatchewan. Morrow (1979) compared leafy spurge planted within a crested wheatgrass and smooth brome perennial grass sod to leafy spurge planted in an area without any plant interference. He found that the perennial grasses reduced leafy spurge plant height as well as the number of shoots. Leafy spurge growing within the perennial grass sod did not set seed nor vegetatively reproduce during the first two growing seasons as did the leafy spurge growing free from plant interference. Competition for soil moisture was found to be an important factor limiting the growth and spread of leafy spurge within the perennial grass sod. When grown as monocultures, brome grass was unable to compete with leafy spurge at any level of infestation while crested wheatgrass could limit the rate of increase in sparse stands of leafy spurge (Selleck *et al.* 1962). When light was limiting under heavy grass cover or in aspen groves, the proportion of flowering shoots of leafy spurge was found to decrease (Selleck *et al.* 1962). Thrasher *et al.* (1963) found that the seeding of several forage grasses decreased the number of Canada thistle plants after 2 years and thistle numbers were inversely proportional to the yield of grass species.

In contrast, results from a study by Coupland and Alex (1954) suggest that the interfering species present had no effect in restricting the extent of the leafy spurge root system. They found that the production of leafy spurge underground parts averaged 30.7 % greater under a seeded mixed crested wheatgrass and smooth brome stand than under cultivation. In fact, the greatest

weights of leafy spurge below-ground parts were present in native grasslands as compared with native meadows, native trees and shrubs, cultivated areas, and areas recently abandoned by cultivation in Saskatchewan.

An integration of several weed control practices could achieve greater weed control than is possible with using each of the practices alone, presumably by increasing the stress on the weed. Additionally, various management techniques such as burning, mowing, fertilizing, and selective herbicides can be implemented to favor the growth of desirable species growing with the weed thereby increasing plant interference upon the weed. Several studies have had success with using a combination of weed control practices. The establishment of perennial grasses along with the use of herbicides has shown promise in the control leafy spurge (Whitson *et al.* 1989, Ferrell *et al.* 1992, and Dwight A. Tober, personal communication). Burning followed by an application of picloram resulted in significant control of leafy spurge (McOwen 1990). When mowed at least twice a year, alfalfa has been one of the best competitive crops in the control of Canada thistle (Hodgson 1968). Effective control of Canada thistle was also achieved where perennial forage grasses were grown, mowed twice a year, and sprayed with 2,4-D (Hodgson 1968).

The Minnesota Department of Transportation has recently begun seeding native grasses instead of introduced grasses, such as smooth brome and Kentucky bluegrass, in the roadside rights-of-way (Minnesota Integrated Roadside Resource Management (IRRM) Symposia 1992, 1993). The use of native vegetation would decrease mowing costs and increase wildlife habitat. Because native grasses develop very deep and extensive root systems, they can provide long-term erosion control, can better compete with noxious deep rooted perennial weeds such as leafy spurge and Canada thistle, and provide an unfavorable habitat for the establishment of newly recruited weeds. With providing better weed control, chemical herbicide use would decrease.

The purpose of the present study was to evaluate the interfering ability of several native perennial grasses established within leafy spurge or Canada thistle infestations along with an integration of additional weed management tools such as mowing, fertilizing, burning, and herbicide applications.

Materials and Methods

Greenhouse Experiment

A preliminary experiment was designed to assess the ability of five perennial grass species to interfere with the growth of leafy spurge and Canada thistle in pots grown under greenhouse conditions. The species included three warm season grasses; switchgrass (*Panicum virgatum* L.), little bluestem [*Schizachyrium scoparium* (Michx.) Nash], and big bluestem (*Andropogon*

gerardii Vitman), and two cool season grasses; smooth brome (*Bromus inermis* Leyss.) and Canada wildrye (*Elymus canadensis* L.). Leafy spurge and Canada thistle seeds were collected locally from infestations around the Twin Cities area. Seed for the grass species were obtained from the Minnesota Department of Transportation. All seeds were germinated in the greenhouse in flats of vermiculite:perlite (1:1) at a temperature of 70°F:60°F (70°F during the light span and 60°F during the dark span) in mid October of 1990. No supplemental lighting was present. Seedlings were transplanted 3 weeks later into eight inch plastic pots using a greenhouse standard soil mix and grown in the greenhouse at a temperature of 65°F:60°F. The experimental treatments consisted of ten seedlings of either leafy spurge or Canada thistle grown together with ten grass seedlings. The control treatments consisted of pots containing 10 ("control 10") and 20 ("control 20") leafy spurge or Canada thistle seedlings. There were 3 replicates for each treatment. Dead seedlings were replaced during the 3 weeks following transplantation but not thereafter. Pots were watered daily with tap water.

After approximately 16 weeks, leafy spurge and Canada thistle plants were harvested. Plants were rinsed 2x in tap water followed by a third washing in distilled water to remove all soil debris. Some losses of root tissue occurred for Canada thistle, especially when grown with Canada wildrye and smooth brome grass, due to the entanglement of the root systems. Also, it was impossible to completely remove all of the perlite and peat from the Canada thistle roots. Shoot and root portions of leafy spurge and Canada thistle were separated, placed in paper bags, and dried at 65°C in a drying oven for 1 week. The oven-dried plant parts were combined for each pot, ground using a mortar and pestal, and weighed (Scientech 3300). The mean dry weight of roots and shoots were calculated for each species in each pot. Analysis of variance and Fisher's Protected Least Significant Difference (PLSD) multiple comparison tests were performed using StatView SE+ Graphics software package (Abacus Concepts, Inc).

Field Experiments

Leafy Spurge

Two field experiments were started in June of 1991 to evaluate the interfering ability of several perennial grasses established within a leafy spurge infestation as well as the effects of additional weed management practices such as mowing, fertilizing, burning, and herbicide applications. The field experiments are located in an established leafy spurge infestation at the maintenance facility of the Minnesota Valley National Wildlife Refuge, 5981 E. Highway 101, Shakopee, Minnesota. The site is located in the floodplain of the Minnesota River. The soil is a coarse sand to loamy coarse sand according to the the United States Department of Agriculture textural names. The vegetation consists of *Euphorbia esula* L. as the dominant species with *Amaranthus retroflexus* L., *Chenopodium album* L., *Mollugo verticillata* L., *Oenothera biennis*

L., *Physalis heterophylla* Nees., *Grindelia squarrosa* (Pursh) Dunal., *Verbena stricta* Vent., *Erigeron strigosus* Muhl., *Polygonum pensylvanicum* L., *Berteroa incana* (L.) DC., *Solanum rostratum* Dunal., *Conyza canadensis* (L.) Cronq., and *Artemisia ludoviciana* Nutt. also occurring. Nomenclature follows Gleason and Cronquist (1963). Voucher specimens have been deposited in the University of Minnesota herbarium, St Paul, MN.

Three large leafy spurge patches were plotted. Plot A had dimensions of 24 m x 19 m; Plot B-20 m x 18 m; and Plot C-13 m x 18 m. The initial percent above-ground cover of leafy spurge was determined by averaging the percent cover estimates from a 0.5 m diameter circular hoop tossed 20 times in each of the three plots. Plots B and C were sprayed with glyphosate at 1.4 lbs active ingredient (ai)/acre on June 8, 1991. On June 12, 1991, the three plots were disked. Plot A was used as one experiment consisting of three replicates of eight treatments. Treatment rows were 1 m wide by 19 m long. The treatments included: (1) 'Bozoisky' Russian wildrye (*Psathyrostachys juncea* (Fisch.) Nevski); (2) 'Hakari' mountain brome (*Bromus sitchensis* Trin.); (3) a mixture of 'Luna' pubescent wheatgrass (*Agropyron intermedium* var. *trichophorum* (Link) Halac.), 'Ephraim' crested wheatgrass (*Agropyron cristatum* (L.) Gaertn.), and 'Arriba' western wheatgrass (*Agropyron smithii* Rydb.); (4) a mixture of 'Hakari' mountain brome, 'Tiki' smooth brome (*Bromus inermis* Leyss.), and 'Matua' brome; (5) a mixture of short native prairie grasses-side-oats grama (*Bouteloua curtipendula* (Michx.) Torr.), buffalograss (*Buchloe dactyloides* (Nutt.) Engelm.), and little bluestem (*Schizachyrium scoparium* (Michx.) Nash); (6) a mixture of little bluestem and side-oats grama; (7) little bluestem; and (8) a control-no species seeded. Plots B and C were used together in an experiment consisting of three replicates of eleven treatments. Treatment rows were 1 m wide by 18 m long. The treatments included: (1) a mixture of big bluestem (*Andropogon gerardii* Vitman) and little bluestem; (2) a mixture of switchgrass (*Panicum virgatum* L.) and side-oats grama; (3) a mixture of short native prairie grasses-side-oats grama, buffalograss, and little bluestem; (4) a mixture of tall native prairie grasses-big bluestem, switchgrass, and indiagrass (*Sorghastrum nutans* (L.) Nash); (5) 'Ramsey' alfalfa (*Medicago sativa* L.); (6) a mixture of 'Luna' pubescent wheatgrass, 'Ephraim' crested wheatgrass, and 'Arriba' western wheatgrass; (7) a mixture of 'Hakari' mountain brome, 'Tiki' smooth brome, and 'Matua' brome; (8) 'Bozoisky' Russian wildrye; (9) 'Luna' pubescent wheatgrass; (10) buffalograss; (11) a control-no species seeded.

Information on the source and origin of the seed is presented in Appendix A, (Table A). In both experiments the treatments were seeded at 100 pure live seed (PLS) lbs/acre with 'Starter' oats (*Avena sativa* L.) at 20 lbs/acre as a cover crop. In treatments containing a mixture of grasses, the total of all seed was 100 PLS lbs/acre. The placement of treatment rows within the plots was randomly determined. Seed was spread and raked in by hand on June 18-21, 1991.

The fluffy seed mixtures were first mixed with Milorganite fertilizer 6-2-0 (Milorganite Division - MMSD, Milwaukee, Wisconsin) to aid in even dispersal.

In the second year of the study several management techniques were used to promote grass establishment and reduce leafy spurge. A burn was conducted on May 19, 1992 on Plot BC. An attempt was made to burn Plot A, but it would not burn due to a low fuel load. Herbicides were applied in 4.75 m wide blocks in Plot A and in 4.50 m wide blocks in Plot BC across all species treatment rows. The herbicide treatments included: (1) picloram at 1 lb ai/acre applied on June 25, 1992; (2) picloram + 2,4-D at 0.25 lb ai/acre + 1 lb ai/acre, respectively, applied on June 25, 1992; (3) imazethapyr at 0.25 lb ai/acre applied on October 5, 1992; and (4) control- left untreated. Herbicides were applied using a backpack sprayer. Both Plot A and Plot BC were mowed to a height of 6-8 inches on July 31, 1992 and fertilized (Greenview Wintergreen 10-16-20) on October 5, 1992.

The percent cover of leafy spurge was monitored throughout each growing season (7-22-91, 9-11-91, 5-7-92, 7-16-92, 9-1-92, 5-7-93, 7-10-93, 9-1-93). Estimates of percent cover were determined using a 0.5 m diameter hoop tossed ten times along the length of each grass treatment row (N=30 for each grass treatment). After application of the herbicide treatments, percent cover was determined by three tosses of the 0.5 m diameter hoop into each herbicide treatment block of each grass treatment row (N=9 for each grass-herbicide treatment). The percent cover estimates per treatment were averaged. In addition, the degree of grass establishment in each herbicide treatment block of each grass treatment row was determined during the 1993 field season (5-7-93 and 9-1-93). Grass establishment was judged to be either sparse, medium, or good and coded as 1, 2, or 3, respectively. The coded categories were subject to statistical analyses. Analysis of variance, Fisher's Protected Least Significant Difference (PLSD) multiple comparison test, and regression analyses were performed using StatView SE+ Graphics software package (Abacus Concepts, Inc).

Canada Thistle

Two separate field experiments were established to evaluate the interfering ability of several native prairie grass mixtures planted within Canada thistle infestations. The field experiments are located in the right-of-way of Interstate 35W and Highway 97 in Forest Lake, MN, and in the right-of-way of Rt 14 in Owatonna, MN.

At the Forest Lake site, the vegetation consists of *Cirsium arvense* (L.) Scop., *Setaria viridis* (L.) Beauv., *Vicia villosa* Roth., *Lychnis alba* Mill., *Rumex mexicanus* Meissn., *Verbascum Thapsus* L., *Verbena hastata* L., *Asclepias incarnata* L., *Erysimum cheiranthoides* L., *Chenopodium album* L., *Potentilla norvegica* L., *Polygonum Convolvulus* L., *Polygonum Persicaria* L., *Bromus inermis* Leyss., *Agrostis gigantea* Roth., and *Phalaris arundinacea* L.

Nomenclature follows Gleason and Cronquist (1963). Voucher specimens have been deposited in the University of Minnesota herbarium, St Paul, MN. The soil is a fine sandy loam according to the United States Department of Agriculture textural names.

The experiment at Forest Lake was set up as a split-plot design. Twenty 4 m x 6 m plots were positioned in 4 rows of 5 plots each. On May 31, 1990, the existing vegetation was removed from all but one randomly chosen plot (control) in each row using a sod cutter, leaving a 1 to 2 meter wide strip of undisturbed vegetation between the plots. Each plot was divided into four 2 m x 3 m subplots. Glyphosate was applied at commercial rates on May 28, 1990 to one of the control plots and fourteen of the non-control plots. With the exception of the four control plots, each plot received four randomly assigned native grass treatments seeded into the subplots at a final rate of 2 seeds/square inch on June 1, 1990. Seed was first mixed with Milorganite fertilizer 6-2-0 (Milorganite Division - MMSD, Milwaukee, Wisconsin), spread and then raked in by hand. The native grass treatments (subplots) included: (A) switchgrass + big bluestem : little bluestem : side-oats grama + blue grama (*Bouteloua gracilis* (HBK.) Lag.) in a 1 : 2 : 1 ratio; (B) switchgrass; (C) switchgrass + big bluestem : little bluestem + side-oats grama + blue grama in a ratio of 2 : 1; and (D) switchgrass + big bluestem + little bluestem : side-oats grama + blue grama in a ratio of 1 : 2.

Plots were periodically mowed to promote grass establishment. (8-9-90, 7-2-91, 6-8-92). Due to poor establishment of the native grass species, the subplots were overseeded by hand on October 14, 1991. Herbicide treatments were applied, using a backpack sprayer, to the rows of plots on July 9, 1992. Herbicide treatments included: (A) 2,4-D at 2 lbs ai/acre; (B) 2,4-D + picloram at 1 lb ai/acre + 0.25 lb ai/acre, respectively; (C) 2,4-D + dicamba at 0.5 lb ai/acre + 0.25 lb ai/acre, respectively; and (D) no herbicides.

The above-ground percent cover of Canada thistle was monitored throughout each growing season (7-18-90, 6-24-91, 9-6-91, 6-2-92, 9-8-92, 6-10-93, 9-8-93). Estimates of percent cover were determined using a 1 m diameter hoop tossed once into each subplot. The percent cover estimates were averaged per grass treatment (N=16 prior to herbicide application) and per grass-herbicide treatment (N=4 after herbicide application). Analysis of variance and Fisher's Protected Least Significant Difference (PLSD) multiple comparison tests were performed using StatView SE+ Graphics software package (Abacus Concepts, Inc).

At the Owatonna site, the vegetation consists of *Cirsium arvense* (L.) Scop., *Trifolium pratense* L., *Trifolium hybridum* L., *Equisetum arvense* L., *Hibiscus Trionum* L., *Ambrosia artemisiifolia* L., *Solanum nigrum* L., *Brassica Kaber* (DC.) L. Wheeler, *Amaranthus hybridus* L., *Setaria lutescens* (Weigel) Hubb., *Setaria faberi* Herrm., *Panicum capillare* L., *Erysimum cheiranthoides* L., *Chenopodium album* L., *Lotus corniculatus* L., *Phalaris arundinacea* L.,

Phleum pratense L., *Bromus inermis* Leyss., and *Polygonum pensylvanicum* L. Nomenclature follows Gleason and Cronquist (1963). Voucher specimens have been deposited in the University of Minnesota herbarium, St Paul, MN. The soil is classified as a loam according to the United States Department of Agriculture textural names.

A 90 m x 25 m area in the right-of-way was disked on May 17, 1991 to remove the existing vegetation. The experiment consisted of four repetitions of eleven treatments. Treatment plots were in 2 m wide by 23 m long rows. The treatments included: (1) big bluestem; (2) switchgrass; (3) 'Spredor 2' alfalfa; (4) switchgrass + big bluestem; (5) switchgrass + little bluestem; (6) little bluestem + big bluestem; (7) side-oats grama + indiangrass; (8) buffalograss + indiangrass; (9) a mixture of short native prairie grasses-side-oats grama, buffalograss, and little bluestem; (10) a mixture of tall native prairie grasses-big bluestem, switchgrass, and indiangrass; and (11) control-no species seeded. Information on the source and origin of the seed is presented in Appendix A, (Table A).

The treatments were seeded at 100 pure live seed (PLS) lbs/acre with 'Starter' oats (*Avena sativa* L.) at 20 lbs/acre as a cover crop. In treatments containing a mixture of grasses, the total of all seed was 100 PLS lbs/acre. The placement of treatments was randomly determined. Seed was spread and raked in by hand during May 21 to June 7, 1991. Seed treatments were first mixed with Milorganite fertilizer 6-2-0 (Milorganite Division - MMSD, Milwaukee, Wisconsin) to aid in even dispersal. To promote the establishment of the native grass treatments, the field site was periodically mowed to a height of 8 inches (7-30-91, 6-9-92, 8-7-92) and burned on November 19, 1992.

The above-ground percent cover of Canada thistle was monitored throughout each growing season (7-15-91, 9-16-91, 5-27-92, 7-21-92, 9-24-92, 5-21-93, 7-21-93, 9-24-93). Estimates of percent cover were determined using a 0.5 m diameter hoop tossed ten times along the length of each grass treatment row (N=40 for each grass treatment). The percent cover estimates were averaged per treatment. Analysis of variance and Fisher's Protected Least Significant Difference (PLSD) multiple comparison tests were performed using StatView SE+ Graphics software package (Abacus Concepts, Inc).

Analysis of Soil Properties

Soil from each of the three study sites was collected and analyzed for several physical and chemical properties. Soil samples were collected from within the control areas (no species seeded and no herbicides applied) of Plots A, B, and C at the Minnesota Valley National Wildlife Refuge, and from the Forest Lake site on October 2, 1992. Soil samples were collected from an area just outside the treatment rows at the Owatonna site on September 24, 1992. Five 10 cm cores were taken for each sample using a 22 mm diameter corer. Soil samples were placed in

plastic bags and then transferred to paper bags for air drying at the laboratory. The dried soil samples were passed through a 2 mm sieve. Hydrogen ion activity was determined using a Cole-Parmer Series 5986 Chemcadet pH/mV meter with a Ag/AgCl combination pH electrode, according to the method of Wilde *et al.* (1972). Percent nitrogen (Kjeldahl nitrogen without nitrate reduction), extractable phosphate (Bray P-1), total organic carbon (soils without carbonates), and exchangeable Ca, Mg, Na, and K (equilibrium with ammonium acetate) determinations were performed by the University of Minnesota Department of Soil Science Research Analytical Laboratory. Particle size distribution, determined by sedimentation, was conducted by the University of Minnesota Soil Survey Laboratory.

Results

Greenhouse Experiment

The two cool-season grasses, Canada wildrye and smooth brome, established well and significantly reduced the dry weight of leafy spurge roots and Canada thistle roots and shoots as compared to the control treatments (Table 2.1). The "control 20" treatment was always significantly less than the "control 10" treatment and represents a better control since the total number of plants per pot in all the grass treatments is 20. Of the warm-season grasses, little bluestem and switchgrass both resulted in a significant increase in Canada thistle root dry weight as compared to the "control 20" treatment.

Field Experiments

Leafy Spurge

The analysis of soil properties for Plots A, B, and C at the Minnesota Valley National Wildlife Refuge are presented in Table 2.2. The soil data reveals the sandy, nutrient poor conditions at the site. Generally, the soil conditions present in each of the three plots were relatively similar with the notable exception of higher levels of phosphorous in Plots B and C as compared to Plot A.

The percent cover of leafy spurge taken in June 1991 in Plot A prior to disking was $46.0\% \pm 4.6(\text{SEM})$. The mean percent cover of leafy spurge during the first year of grass establishment prior to herbicide treatments in Plot A is presented in Table 2.3. Although statistically significant differences in percent cover of leafy spurge among treatments did occur as early as 1 month (July 1991) and 3 months (September 1991) after seed sowing, it was not until May 1992 that any grass treatment had significantly lower leafy spurge percent cover values than the control. Little bluestem as a monoculture and as mixtures with side-oats grama and

buffalograss appeared to be most effective at reducing the cover of leafy spurge during the grass establishment phase.

The effects of grass and herbicide treatments on the percent cover of leafy spurge for Plot A during the 1993 field season are presented in Tables 2.4-2.6 for May, July, and September, respectively. Little bluestem as a monoculture and as mixtures with side-oats grama and buffalograss continued to be very effective at reducing leafy spurge cover and by July and September were the only grass treatments having any statistical significance. The effects of the herbicides appear to be very short-lived. In May, all herbicide treatments significantly reduced the percent cover of leafy spurge with both picloram and imazethapyr being extremely effective. By September, there were no statistically significant differences among the herbicide treatments.

The percent cover of leafy spurge taken in June 1991 in Plots B and C were 33.2 ± 4.2 , and 52.5 ± 3.9 , respectively. The mean percent cover of leafy spurge during the first year of grass establishment prior to herbicide treatments in Plot BC is presented in Table 2.7. Although statistically significant differences in percent cover of leafy spurge among the grass treatments were present in July and September of 1991, no grass treatment had significantly lower spurge cover values than the control. By May (1992) there was a large drop in spurge cover across all grass treatments in Plot BC. This drop in spurge cover did not occur in Plot A.

The effects of grass and herbicide treatments on the percent cover of leafy spurge for Plot BC during the 1993 field season are presented in Tables 2.8-2.10 for May, July, and September, respectively. The percent cover of leafy spurge remained very low throughout the entire 1993 growing season. In both July and September there were significant grass treatment effects, but there were no grass treatments that were significantly lower in spurge cover than the control. The herbicides picloram and imazethapyr significantly reduced the cover of leafy spurge throughout the season. The 2,4-D+ picloram herbicide treatment resulted in spurge cover values significantly greater than those of the control during both the May and July sampling periods.

The degree of establishment of the grass treatments in Plots A and BC are presented in Tables 2.11 and 2.12 for Plot A and Plot BC, respectively. In Plots A and BC there were no statistically significant herbicide effects on grass establishment. In Plot A the grass treatments containing little bluestem alone and in mixtures established very well, while Russian wildrye and the bromes alone and in mixtures showed poor establishment. In Plot BC the grass treatments BB+LB, SW+SOG, SOG+BUF, BB+SW+IND, and Luna pubescent wheatgrass overall had very good establishment within the treatment rows although the establishment of switchgrass within the mixtures was rather poor. Better grass establishment occurred in the Luna pubescent wheatgrass treatment than in the wheatgrass mixture. Both Russian wildrye and alfalfa had extremely poor establishment in Plot BC.

The relationship between degree of grass establishment and the percent cover of leafy spurge is depicted in Figure 2.1. There is a negative correlation between leafy spurge cover and the degree of grass establishment. A large proportion of the variance of leafy spurge cover can be predicted from the degree of grass establishment (compare R^2 values) for Plot A but not for Plot BC. Also, the slope of the regression equation is significantly different from 0 at the 95 % level for Plot A but not for Plot BC.

Canada Thistle

Visual inspection revealed the establishment of grass treatments as being very poor and patchy within the field plots at the Forest Lake site. Overseeding the plots in October of 1991 did not appear to improve establishment. Blue grama and little bluestem never established. By September of 1993, only five clumps of big bluestem and a small patch of switchgrass could be found among the entire twenty plots. Almost all plots contained a large cover of reed canary grass. The mean percent cover of Canada thistle in each of the grass treatment plots during the first two years prior to herbicide treatments are presented in Table 2.13. Only in June of 1992 did any statistically significant treatment effects occur. Treatments A and C both had significantly greater thistle cover than the controls. Analysis of variance of the data from September 1992 (data not presented) and the 1993 field season revealed no significant herbicide or grass treatment effects (Table 2.14).

The establishment of the grasses at the Owatonna site was also very poor and patchy. Buffalograss never established. Alfalfa established well initially but began to decline in July of 1993. The establishment of indiangrass appeared to improve within the three years of monitoring. A large cover of reed canary grass was present at the site. The mean percent cover of Canada thistle in each of the grass treatment plots is presented in Table 2.15. Although some differences in cover among the grass treatments are statistically significant, no grass treatment was found to have significantly lower thistle cover values than the control.

Table 2.1. Interference of perennial grasses with leafy spurge and Canada thistle grown together under greenhouse conditions.

Treatment	Mean dry weight of plant part (g)			
	Leafy spurge		Canada thistle	
	Shoots	Roots	Shoots	Roots
control (10)	0.024 a*	0.081 a	0.360 a	0.514 a
little bluestem	0.020 a	0.054 b	0.293 ab	0.410 b
switchgrass	0.016 a	0.043 bc	0.237 b	0.392 b
big bluestem	0.021 a	0.068 ab	0.214 bc	0.357 bc
control (20)	0.013 a	0.043 b	0.212 bc	0.282 c
Canada wildrye	0.013 a	0.017 cd	0.114 cd	0.143 d
smooth brome	0.005 a	0.014 d	0.091 d	0.085 d

*Means within a column followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Table 2.2. Physical and chemical properties of soil samples collected from the Minnesota Valley National Wildlife Refuge, Forest Lake and Owatonna field sites.

	MN Valley National Wildlife Refuge Site			Forest Lake Site	Owat- onna Site
	Plot A	Plot B	Plot C		
% N	0.10	0.10	0.10	0.46	0.29
% organic carbon	1.48	1.13	1.16	5.60	3.68
pH	5.46	5.89	6.50	7.03	5.90
P (ppm)	7	36	38	20	15
K (ppm)	48.02	90.8	39.7	248.9	216.3
Ca (ppm)	998.6	948.3	774.0	3515.1	3051.3
Mg (ppm)	181.6	200.7	153.4	371.6	553.9
Na (ppm)	6.7	4.8	4.6	10.9	14.5
% sand	86		90	73	29
% silt	8		6	15	47
% clay	6		4	12	24

Table 2.3. Mean percent cover of leafy spurge during the first year of grass establishment in Plot A from the Minnesota Valley National Wildlife Refuge site.

Grass Treatment*	Mean % Cover Leafy Spurge		
	July 1991	September 1991	May 1992
Russian wildrye	16.8 bcd**	20.0 bc	22.5 bc
Hakari mountain brome	15.6 cd	24.2 abc	22.8 bc
wheatgrasses (LP+EC+AW)	25.6 a	25.8 ab	27.9 ab
bromes (HM+TS+MB)	24.0 ab	29.8 a	27.3 ab
SOG+BUFF+LB	20.2 abc	22.5 bc	18.8 c
LB+SOG	10.4 d	18.7 c	17.9 c
little bluestem	17.1 bcd	18.3 c	18.7 c
control	15.6 cd	23.7 bc	32.0 a

*LB=little bluestem, SOG=side-oats grama, BUF=buffalograss, LP=Luna pubescent wheatgrass, EC=Ephraim crested wheatgrass, AW=Arriba western wheatgrass, HM=Hakari mountain brome, TS=Tiki smooth brome, and MB=Matua brome grass.

**Means within a column followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Table 2.4. Effects of grass and herbicide treatments on the % cover of leafy spurge at the Minnesota Valley National Wildlife Refuge site for Plot A in May 1993.

Plot A-May 1993

Grass Treatment*	Mean % Cover Leafy Spurge				
	no herbicide	imazethapyr	24D+ picloram	picloram	Totals***
Russian wildrye	17.2	1.4	11.1	6.6	9.1 b
Hakari mountain brome	17.8	0.7	9.7	3.2	7.8 b
wheatgrasses (LP+EC+AW)	17.2	2.2	13.9	2.0	8.8 b
bromes (HM+TS+MB)	14.4	2.6	14.7	2.4	8.5 b
SOG+BUFF+LB	12.4	3.0	5.4	4.0	6.2 bc
LB+SOG	5.2	4.6	6.7	1.8	4.6 c
little bluestem	8.9	3.7	4.3	2.1	4.8 c
control	24.4	5.1	17.2	6.1	13.2 a
Totals**	14.7 a	2.9 c	10.4 b	3.5 c	

*LB=little bluestem, SOG=side-oats grama, BUF=buffalograss, LP=Luna pubescent wheatgrass, EC=Ephraim crested wheatgrass, AW=Arriba western wheatgrass, HM=Hakari mountain brome, TS=Tiki smooth brome, and MB=Matua brome grass.

**Mean of data combined for grass treatment.

***Mean of data combined for herbicide treatment.

Means within the "Totals" column and row followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Table 2.5. Effects of grass and herbicide treatments on the % cover of leafy spurge at the Minnesota Valley National Wildlife Refuge site for Plot A in July 1993.

Plot A-July 1993

Grass Treatment*	Mean % Cover Leafy Spurge				
	no herbicide	imazethapyr	24D+ picloram	picloram	Totals***
Russian wildrye	37.2	21.1	24.4	27.2	27.5 a
Hakari mountain brome	31.1	11.7	27.8	17.2	21.9 a
wheatgrasses (LP+EC+AW)	28.3	20.6	32.2	22.2	25.8 a
bromes (HM+TS+MB)	27.2	11.9	43.9	18.3	25.3 a
SOG+BUFF+LB	21.1	12.8	15.0	14.1	15.8 b
LB+SOG	11.1	12.4	16.7	6.7	11.7 b
little bluestem	15.6	11.1	15.0	14.1	13.9 b
control	33.9	27.8	27.2	16.1	26.3 a
Totals**	25.7 a	16.2 b	25.3 a	17.0 b	

*LB=little bluestem, SOG=side-oats grama, BUF=buffalograss, LP=Luna pubescent wheatgrass, EC=Ephraim crested wheatgrass, AW=Arriba western wheatgrass, HM=Hakari mountain brome, TS=Tiki smooth brome, and MB=Matua brome grass.

**Mean of data combined for grass treatment.

***Mean of data combined for herbicide treatment.

Means within the "Totals" column and row followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Table 2.6. Effects of grass and herbicide treatments on the % cover of leafy spurge at the Minnesota Valley National Wildlife Refuge site for Plot A in September 1993.

Plot A-September 1993

Grass Treatment*	Mean % Cover Leafy Spurge				
	no herbicide	imazethapyr	24D+ picloram	picloram	Totals***
Russian wildrye	22.2	17.2	15.6	20.0	18.8 a
Hakari mountain brome	16.1	10.6	25.6	19.4	17.9 a
wheatgrasses (LP+EC+AW)	12.8	13.6	17.2	20.6	16.0 a
bromes (HM+TS+MB)	16.1	12.2	24.4	16.1	17.2 a
SOG+BUFF+LB	12.8	11.1	8.9	14.4	11.8 b
LB+SOG	7.4	7.8	8.3	6.7	7.6 c
little bluestem	8.9	8.3	11.7	8.9	9.4 bc
control	21.7	23.9	12.8	14.4	18.2 a
Totals**	14.8 a	13.1 a	15.6 a	15.1 a	

*LB=little bluestem, SOG=side-oats grama, BUF=buffalograss, LP=Luna pubescent wheatgrass, EC=Ephraim crested wheatgrass, AW=Arriba western wheatgrass, HM=Hakari mountain brome, TS=Tiki smooth brome, and MB=Matua brome grass.

**Mean of data combined for grass treatment.

***Mean of data combined for herbicide treatment.

Means within the "Totals" column and row followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Table 2.7. Mean percent cover of leafy spurge during the first year of grass establishment in Plot BC from the Minnesota Valley National Wildlife Refuge site.

Grass Treatment*	Mean % Cover Leafy Spurge		
	July 1991	September 1991	May 1992
BB+LB	11.7 ab**	9.8 de	0.6 a
SW+SOG	9.5 abcd	11.9 cde	1.5 a
SOG+BUF+ LB	10.5 abcd	20.8 ab	1.5 a
BB+SW+IND	6.5 bcd	5.1 e	2.3 a
alfalfa	11.1 abc	13.5 cd	0.6 a
wheatgrasses (LP+EC+AW)	14.1 a	17.5 bc	1.2 a
bromes (HM+TS+MB)	12.6 ab	26.8 a	1.2 a
Russian wildrye	6.7 bcd	11.2 cde	0.6 a
Luna pubescent wheatgrass	4.6 cd	16.8 bc	0.7 a
buffalograss	4.0 d	9.5 de	0.6 a
control	7.0 bcd	10.8 cde	0.8 a

*BB=big bluestem, SW=switchgrass, IND=indiangrass, LB=little bluestem, SOG=sideoats grama, BUF=buffalograss, LP=Luna pubescent wheatgrass, EC=Ephraim crested wheatgrass, AW=Arriba western wheatgrass, HM=Hakari mountain brome, TS=Tiki smooth brome, and MB=Matua brome grass.

**Means within a column followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Table 2.8. Effects of grass and herbicide treatments on the % cover of leafy spurge at the Minnesota Valley National Wildlife Refuge site for Plot BC in May 1993.

Plot BC-May 1993

Grass Treatment*	Mean % Cover Leafy Spurge				
	no herbicide	imazethapyr	24D+ picloram	picloram	Totals***
BB+LB	0.8	0	1.9	0.3	0.8 a
SW+SOG	1.0	0.2	2.1	0	0.8 a
SOG+BUF+ LB	1.0	0.6	2.9	0	1.1 a
BB+SW+IND	1.9	0.1	1.9	0	1.0 a
alfalfa	0.6	0	1.9	0	0.6 a
wheatgrasses (LP+EC+AW)	1.3	0	2.4	0	0.9 a
bromes (HM+TS+MB)	2.2	0.4	3.8	0	1.6 a
Russian wildrye	2.1	0	3.6	0.2	1.5 a
Luna pubescent wheatgrass	1.1	0	0.4	0	0.4 a
buffalograss	0.4	0.8	1.3	0	0.6 a
control	0.4	0	2.4	1.1	1.0 a
Totals**	1.2 b	0.2 c	2.2 a	0.1 c	

*BB=big bluestem, SW=switchgrass, IND=indiangrass, LB=little bluestem, SOG=side-oats grama, BUF=buffalograss, LP=Luna pubescent wheatgrass, EC=Ephraim crested wheatgrass, AW=Arriba western wheatgrass, HM=Hakari mountain brome, TS=Tiki smooth brome, and MB=Matua brome grass.

**Mean of data combined for grass treatment.

***Mean of data combined for herbicide treatment.

Means within the "Totals" column and row followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Table 2.9. Effects of grass and herbicide treatments on the % cover of leafy spurge at the Minnesota Valley National Wildlife Refuge site for Plot BC in July 1993.

Plot BC-July 1993

Grass Treatment*	Mean % Cover Leafy Spurge				
	no herbicide	imazethapyr	24D+ picloram	picloram	Totals***
BB+LB	0.2	0.2	1.0	0	0.4 d
SW+SOG	2.4	0.6	5.2	0.6	2.2 bcd
SOG+BUF+ LB	3.3	0	5.0	0	2.1 bcd
BB+SW+IND	1.3	1.1	1.7	0.4	1.1 d
alfalfa	4.7	0.6	4.7	0	2.5 abcd
wheatgrasses (LP+EC+AW)	6.1	0.6	11.1	0	4.4 ab
bromes (HM+TS+MB)	4.4	2.4	8.6	3.9	4.8 a
Russian wildrye	4.3	2.2	6.7	2.2	3.9 abc
Luna pubescent wheatgrass	1.3	0.6	2.2	0.8	1.2 d
buffalograss	3.0	1.3	3.8	0.8	2.2 bcd
control	1.3	2.3	2.1	1.8	1.9 cd
Totals**	3.0 b	1.1 c	4.7 a	1.0 c	

*BB=big bluestem, SW=switchgrass, IND=indiangrass, LB=little bluestem, SOG=side-oats grama, BUF=buffalograss, LP=Luna pubescent wheatgrass, EC=Ephraim crested wheatgrass, AW=Arriba western wheatgrass, HM=Hakari mountain brome, TS=Tiki smooth brome, and MB=Matua brome grass.

**Mean of data combined for grass treatment.

***Mean of data combined for herbicide treatment.

Means within the "Totals" column and row followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Table 2.10. Effects of grass and herbicide treatments on the % cover of leafy spurge at the Minnesota Valley National Wildlife Refuge site for Plot BC in September 1993.

Plot BC-September 1993

Grass Treatment*	Mean % Cover Leafy Spurge				
	no herbicide	imazethapyr	24D+ picloram	picloram	Totals***
BB+LB	4.4	0	1.0	0.6	1.5 c
SW+SOG	1.7	0.2	2.8	0.6	1.3 c
SOG+BUF+LB	2.2	0.2	2.8	0	1.3 c
BB+SW+IND	1.7	0.6	1.9	0	1.0 c
alfalfa	2.1	3.3	2.8	0	2.1 bc
wheatgrasses (LP+EC+AW)	2.8	0.2	3.6	0.2	1.7 c
bromes (HM+TS+MB)	7.4	2.4	7.1	0.8	4.4 a
Russian wildrye	8.0	3.0	3.6	0.6	3.8 ab
Luna pubescent wheatgrass	0.8	0.6	0.2	0.6	0.5 c
buffalograss	3.8	2.4	1.9	0	2.0 bc
control	0.2	0.4	3.9	0.2	1.2 c
Totals**	3.2 a	1.2 b	2.8 a	0.3 b	

*BB=big bluestem, SW=switchgrass, IND=indiangrass, LB=little bluestem, SOG=side-oats grama, BUF=buffalograss, LP=Luna pubescent wheatgrass, EC=Ephraim crested wheatgrass, AW=Arriba western wheatgrass, HM=Hakari mountain brome, TS=Tiki smooth brome, and MB=Matua brome grass.

**Mean of data combined for grass treatment.

***Mean of data combined for herbicide treatment.

Means within the "Totals" column and row followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Table 2.11. Establishment of perennial grasses at the Minnesota Valley National Wildlife Refuge site for Plot A in September 1993.

Plot A-September 1993

Grass Treatment*	Grass Establishment 1=sparse, 2=medium, 3=good				
	no herbicide	imazethapyr	24D+ picloram	picloram	Totals***
Russian wildrye	1	1	1	1	1.0 a
Hakari mountain brome	1	1	1	1.3	1.1 a
wheatgrasses (LP+EC+AW)	1	1.7	2.7	2	1.8 b
bromes (HM+TS+MB)	1	1	1	1.3	1.1 a
SOG+BUFF+LB	2	2.7	3	3	2.7 c
LB+SOG	2	3	3	3	2.8 c
little bluestem	2.7	3	3	2.7	2.8 c
control	1	1	1	1	1.0 a
Totals**	1.5 a	1.8 a	2.0 a	1.9 a	

*LB=little bluestem, SOG=side-oats grama, BUF=buffalograss, LP=Luna pubescent wheatgrass, EC=Ephraim crested wheatgrass, AW=Arriba western wheatgrass, HM=Hakari mountain brome, TS=Tiki smooth brome, and MB=Matua brome grass.

**Mean of data combined for grass treatment.

***Mean of data combined for herbicide treatment.

Means within the "Totals" column and row followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Table 2.12. Establishment of perennial grasses at the Minnesota Valley National Wildlife Refuge site for Plot BC in September 1993.

Plot BC-September 1993

Grass Treatment*	Grass Establishment 1=sparse, 2=medium, 3=good				
	no herbicide	imazethapyr	24D+ picloram	picloram	Totals***
BB+LB	3	3	3	3	3.0 e
SW+SOG	2.3	2.7	2.7	2.7	2.6 d
SOG+BUF+ LB	3	3	2.7	3	2.9 de
BB+SW+IND	3	3	3	2.7	2.9 de
alfalfa	1	1	1	1	1.0 a
wheatgrasses (LP+EC+AW)	1.7	2.3	1.7	2.7	2.1 c
bromes (HM+TS+MB)	1.3	1.3	1.7	2	1.6 b
Russian wildrye	1	1	1	1	1.0 a
Luna pubescent wheatgrass	2.7	2.7	2.7	3	2.8 de
buffalograss	2.3	2	2	1.7	2.0 c
control	1	1	1	1	1.0 a
Totals**	2.0 a	2.1 a	2.0 a	2.2 a	

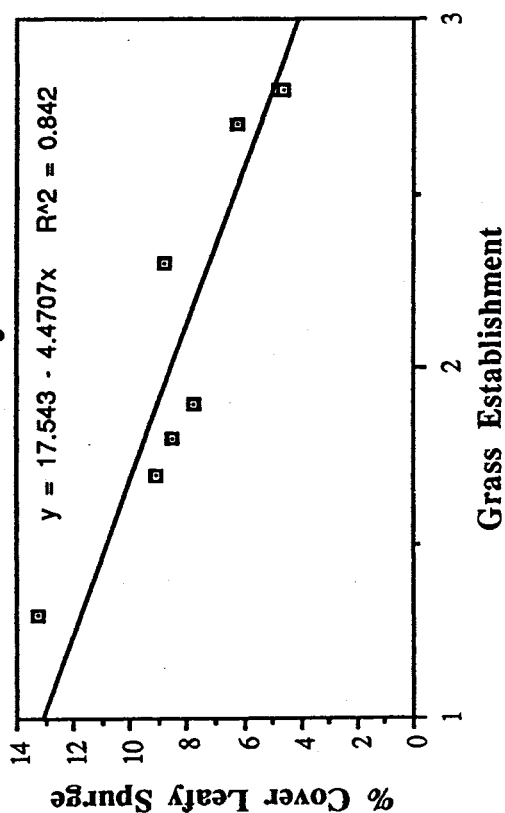
*BB=big bluestem, SW=switchgrass, IND=indiangrass, LB=little bluestem, SOG=side-oats grama, BUF=buffalograss, LP=Luna pubescent wheatgrass, EC=Ephraim crested wheatgrass, AW=Arriba western wheatgrass, HM=Hakari mountain brome, TS=Tiki smooth brome, and MB=Matua brome grass.

**Mean of data combined for grass treatment.

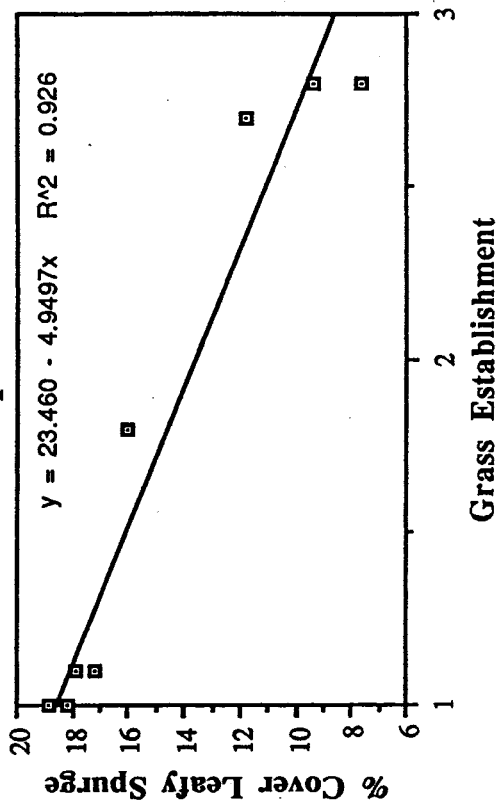
***Mean of data combined for herbicide treatment.

Means within the "Totals" column and row followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

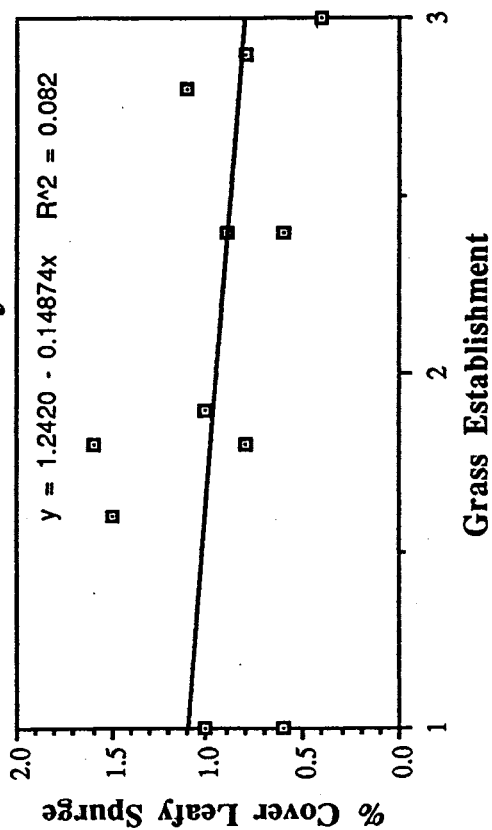
Plot A-May 1993



Plot A-September 1993



Plot BC-May 1993



Plot BC-September 1993

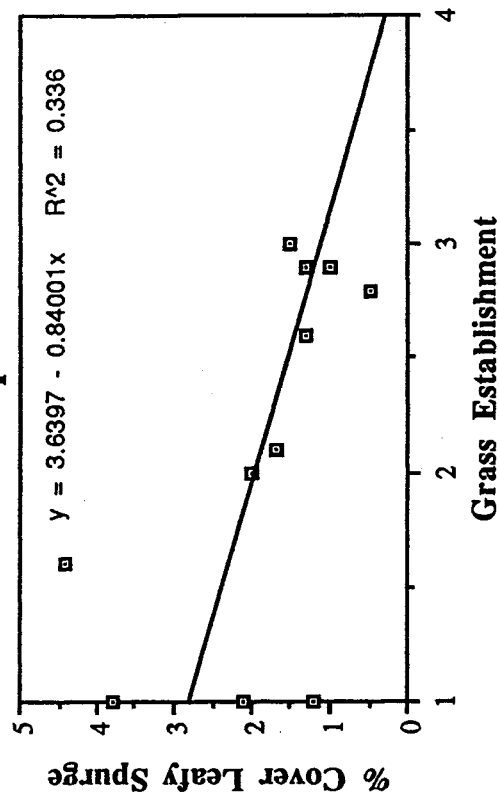


Figure 2.1. Regression analysis of degree of grass establishment and percent cover of leafy spurge in Plots A and BC from the Minnesota Valley National Wildlife Refuge site during May and September of 1993. The grass establishment ratings are; 1=sparse; 2=medium; and 3=good.

Table 2.13. Mean percent cover of Canada thistle at the Forest Lake site during the first 2 years of grass establishment.

Grass Treatment*	Mean % Cover of Canada Thistle			
	July 1990	June 1991	September 1991	June 1992
A	37.0 a**	6.3 a	12.2 a	21.7 a
B	26.9 a	12.1 a	15.0 a	14.4 ab
C	32.3 a	4.4 a	7.8 a	22.3 a
D	43.7 a	9.4 a	9.1 a	14.4 ab
Control	30.7 a	7.9 a	5.6 a	2.6 b

*Grass treatment A= switchgrass + big bluestem : little bluestem : side-oats grama + blue grama in a 1 : 2 : 1 ratio; Grass treatment B= switchgrass; Grass treatment C= switchgrass + big bluestem : little bluestem + side-oats grama + blue grama in a ratio of 2 : 1; Grass treatment D= switchgrass + big bluestem + little bluestem : side-oats grama + blue grama in a ratio of 1 : 2 and Control=no grasses planted.

**Means within a column followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Table 2.14. Effects of grass and herbicide treatments on the % cover of Canada thistle at the Forest Lake site.*

Herbicide Treatment	Mean % Cover of Canada Thistle									
	Grass Treatment A**		Grass Treatment B		Grass Treatment C		Grass Treatment D		Control	
	June 1993	Sept. 1993	June 1993	Sept. 1993	June 1993	Sept. 1993	June 1993	Sept. 1993	June 1993	Sept. 1993
2,4-D (2 lbs/acre)	10	15	1.3	3.8	5.0	1.3	20.5	17.5	0	5.0
2,4-D + picloram (1 + 0.25 lbs/acre)	0	8.8	0	5.0	0	1.3	0.3	3.8	9.3	41.3
2,4-D + dicamba (0.5 + 0.25 lb/acre)	1.3	3.8	2.5	2.5	7.5	2.5	0.5	2.5	0	0
no herbicide	4.3	8.8	2.5	3.0	13.8	22.5	2.3	2.5	0	0

*Two-factor ANOVA revealed no significant ($P < 0.05$) herbicide or grass treatment effects for June or September 1993.

**Grass treatment A = switchgrass + big bluestem : little bluestem : side-oats grama + blue grama in a 1 : 2 : 1 ratio; Grass treatment B = switchgrass; Grass treatment C = switchgrass + big bluestem : little bluestem + side-oats grama + blue grama in a ratio of 2 : 1; Grass treatment D = switchgrass + big bluestem + little bluestem : side-oats grama + blue grama in a ratio of 1 : 2 and Control = no grasses planted.

Table 2.15. Effects of grass treatments on the % cover of Canada thistle at the Owatonna site.

Grass Treatment*	Mean % cover of Canada thistle									
	July 1991	September 1991	May 1992	July 1992	September 1992	May 1993	July 1993	September 1993		
BB	7.8 a**	8.2 a	3.8 ab	5.8 a	4.6 a	1.8 abc	4.0 a	6.0 a		
SW	4.3 a	8.3 a	2.5 a	3.1 a	4.7 a	2.8 bcde	8.4 bc	11.1 bc		
ALF	7.4 a	7.4 a	4.9 ab	3.4 a	4.1 a	0.7 a	3.7 a	7.3 ab		
BB + SW	7.1 a	6.4 a	6.0 bcd	6.2 a	4.5 a	3.8 de	8.9 c	7.2 ab		
LB + SW	7.1 a	9.1 a	3.2 ab	3.8 a	5.2 a	1.8 abc	4.1 ab	6.6 ab		
LB + BB	11.4 a	7.8 a	3.2 ab	4.5 a	4.0 a	1.2 ab	7.6 abc	8.5 abc		
SOG + IND	11.7 a	15.9 b	8.6 d	7.4 a	6.1 a	2.1 abcd	6.8 abc	6.0 a		
BUF + IND	12.2 a	12.0 ab	5.2 abc	6.3 a	5.6 a	4.3 e	9.9 c	11.2 bc		
LB + SOG + BUF	14.9 a	15.9 b	8.5 cd	7.7 a	7.2 a	3.1 cde	9.1 c	11.4 bc		
BB + SW + IND	6.7 a	7.6 a	4.8 ab	6.5 a	6.3 a	3.4 cde	10.2 c	12.4 c		
control	9.1 a	9.0 a	5.2 abcd	5.9 a	3.6 a	2.4 abcd	3.8 a	6.7 ab		

*BB= big bluestem, SW=switchgrass, ALF=alfalfa, LB=little bluestem, SOG=side-oats grama, IND=indiangrass, and BUF=buffalograss

**Means within a column followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Discussion

Greenhouse Experiment

Of the five grass species evaluated for interfering ability with leafy spurge and Canada thistle, only the two cool-season grasses, Canada wildrye and smooth brome, established well in the pots. Since the experiment was conducted in the greenhouse from November to February with no additional lighting and a maximum temperature of only 65°F, the growing conditions would thus favor the cool-season species. Canada wildrye and smooth brome were the only species found to negatively interfere with the growth of leafy spurge and Canada thistle seedlings. Since the warm-season grasses did not establish well, their interfering ability with leafy spurge and Canada thistle could not be adequately determined.

The findings that the mean root dry weight of Canada thistle seedlings growing with little bluestem and switchgrass were significantly greater than the "control 20" treatment, does not support the fact that little bluestem and switchgrass are stimulatory to Canada thistle since the thistle root dry weight values from both grass treatments were still significantly less than the "control 10" treatment. The results rather suggest that Canada thistle interferes more with itself than with either little bluestem or switchgrass which is not surprising since the resource requirements of Canada thistle would be exactly matched by other Canada thistle plants.

Field Experiments

Leafy Spurge

The large drop in leafy spurge cover that occurred in May of 1992 in Plot BC, but not in the area immediately outside the plots or in Plot A, can be most likely explained by the application of glyphosate at 1.4 lbs ai/acre to Plot BC during site preparation in June of 1991. The reason for the apparent delayed effect of glyphosate is not fully understood, especially since it is readily broken down and does not persist in soil (Herbicide Handbook 1989). A possible explanation could be that the population of leafy spurge which appeared immediately following the site preparation represented a flush of seedlings which, due to some factor such as a harsh winter or competition from the establishing grasses, did not survive the winter. Since the spring application of glyphosate followed by disking had eliminated most of the older established spurge plants, the site was left with little spurge the following spring. There was little difference in soil properties between the three Plots with the exception of the relatively higher levels of phosphorous in Plots B and C.

In Plots A and BC significant grass treatment effects did occur after only one month following seed sowing. Although germinating seeds are known to release potentially inhibiting phytotoxins (Friedman and Waller 1983, Schenck and Stotzky 1975), our results indicated that the spurge cover was significantly greater in several of the grass treatments as compared to the

controls. It is more likely that the treatment effects at this time were merely artifacts of the inherent patchiness of leafy spurge although care was taken to establish the field plots within relatively uniform spurge patches. Inhibitory effects of the three grass treatments; little bluestem, little bluestem + side-oats grama, and little bluestem + side-oats grama + buffalograss, began to appear in Plot A during May of 1992, the first spring following sowing. Although the spurge cover values for these three grass treatments remained somewhat stable during this first year, the spurge cover values greatly increased in the control treatments. Disturbances to the underground parts of leafy spurge, such as by disking, are known to stimulate shoot growth (Coupland *et al.* 1955, Selleck *et al.* 1962, Raju *et al.* 1964). Apparently establishing little bluestem, side-oats grama, and buffalograss are able to keep the leafy spurge regrowth in check. The three little bluestem treatments in Plot A continued to reduce the cover of leafy spurge into the third growing season. In Plot BC, there were no consistent effects of any of the grass treatments throughout the entire three years. This inability to discern grass treatment effects may have been due to the very low cover of spurge throughout the plot. Occasionally, significant grass treatment effects did occur but were most likely the result of the patchiness of leafy spurge.

Almost all the prairie grasses native to Minnesota established very well in the sandy, nutrient poor conditions present at our field site with the exception of switchgrass which was extremely sparse in the mixtures and buffalograss which was intermediate in establishment. The poor establishment of switchgrass may have been due to the relatively late seeding date (June) since earlier seedings (mid-April to early May) have proven to be better for establishment (Vassey *et al.* 1985). The introduced grass species were tried to compare to a study performed by Whitson *et al.* (1989) in Wyoming who found that Luna pubescent wheatgrass and Bozoiisky Russian wildrye became well established and provided 93 % control of leafy spurge in tilled plots which had been treated with herbicides prior to seed sowing. In the present study Russian wildrye failed to establish and although Luna pubescent wheatgrass established well (Plot BC), the effects on leafy spurge could not be adequately assessed because of the low cover of spurge present in the plot as previously discussed.

Similar to our results from the greenhouse experiment, those grass species which established well were also the species that reduced the cover of leafy spurge the most in the field. This negative correlation between spurge cover and grass establishment was not very strong for Plot BC probably due to the very small range in cover values. Ferrell *et al.* (1992) also found grass yields correlated with leafy spurge control. Thus, for interfering with leafy spurge, the actual grass species may not be as important as getting a good establishment of a grass species or combination thereof. In a field experiment in North Dakota, all grass species tested did reduce production of leafy spurge to some degree with the exception of one grass species which failed to establish (Dwight A. Tober, personal communication). Therefore, grass species should be

chosen which are adapted to the environmental conditions present at a particular site so that the potential for getting a good establishment is maximized. The use of native Minnesota prairie grasses would be preferred for Minnesota due to their adaptability to this region as well as their deep root systems that can potentially keep the lateral spread of leafy spurge in check.

The late spring application of picloram at 1.0 lb/acre as well as a fall application of imazethapyr at 0.25 lbs/acre were both very effective at reducing the cover of leafy spurge but only for about one year. In field studies in Wyoming, Ferrell and Whitson (1991) found that picloram applied at rates less than 2.0 lbs/acre do need a retreatment program in about two years or less to maintain adequate levels of leafy spurge control. Our results are also consistent with those of Masters *et al.* (1991) who found that imazethapyr applied at 0.25 lbs/acre in the fall provided good control through the following summer with control declining by fall. Although 2,4-D + picloram has been considered the most cost-effective herbicide treatment in the control of leafy spurge (Lym 1991, Lym and Messersmith 1985), it did little to control leafy spurge in the present study. Approximately three weeks following herbicide application, 2,4-D + picloram (0.25 + 1.0 lb ai/acre, respectively) did significantly reduce the cover of leafy spurge (data not presented), but this effect was only short lived and did not persist into the 1993 growing season. Ferrell and Whitson (1989) found that a single application of picloram + 2,4-D (0.25 + 1.0 lb ai/acre, respectively) resulted in only 25% control of leafy spurge after one year while a retreatment resulted in a 51% control of leafy spurge (see also Ferrell 1992 and Sebastian and Beck 1992). None of the three herbicide treatments used in the present study caused any injury to the establishing perennial grasses.

Canada Thistle

At both the Forest Lake and Owatonna sites, grass establishment was extremely poor despite the high seeding rates and our mowing, burning, and reseeding efforts which were designed to favor the establishment of the native grasses. The grass treatments therefore could not even be considered actual treatments. The presence of reed canary grass as well as the unusually wet and cold past two growing seasons contributed greatly to the lack of establishment of the primarily warm-season prairie grasses. Reed canary grass is a perennial grass found in wet habitats and vegetatively spreads by creeping rhizomes (Hitchcock 1971). Reed canary grass dominated the vegetation at both sites by the end of the 1993 growing season, probably due to the recent wet growing conditions. Mn/DOT apparently also has had low success with establishing native prairie plants along roadsides where reed canary grass occurs (Bob Jacobson, Mn/DOT, personal communication).

At Forest Lake, there was a lack of response of Canada thistle to any of the herbicide treatments. The herbicide treatments included the herbicides 2,4-D, dicamba, and picloram.

which are known to be selective in their control of Canada thistle without harming grasses (Moore 1975). 2,4-D at 2 lbs/acre or less has been used to control Canada thistle (Rasmussen 1956, Hodgson 1958, Hodgson 1968) although different ecotypes are known to vary widely in their response to 2,4-D (Hodgson 1970, Hunter and Smith 1972). In a study by Wilson (1981), dicamba + 2,4-D at 0.25 + 0.5 lbs/acre, respectively, was found to control Canada and musk thistle and increase native grass production. In the present study, the lack of herbicide effects may have been due to the tall, dense, vegetation at the site which did not allow for good herbicide contact on the thistle plants. One solution to this problem would be to mow the site just prior to applying herbicides so as to reduce the non-target vegetation intercepting the herbicides thereby allowing more herbicides to reach Canada thistle. Alternatively, the herbicide rates could be increased.

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Chapter 3. Effects of Late Season Herbicide Applications on the Elongation and Growth of Leafy Spurge Vegetative Buds.

Abstract

Field and laboratory experiments were conducted to investigate the effects of a late season application of the herbicides picloram and glyphosate on leafy spurge crown buds. The phenology of leafy spurge crown buds was also studied to determine when the crown buds would potentially be most vulnerable to a herbicide application. Crown bud growth was found to be a gradual process beginning shortly after flowering in mid-June and obtaining maximum size during senescence in October. Both picloram (1.0 lb ai/acre) and glyphosate (1.0 lb ai/acre) applied to senescing leafy spurge in the field in October significantly inhibited shoot expansion when grown under favorable conditions in the laboratory. Picloram applied directly to crown buds of senesced leafy spurge in the laboratory significantly inhibited bud growth. An experiment using ^{14}C -picloram applied directly to crown buds at a rate approximating a field application of 0.5 lb ai/acre, indicated that picloram could be directly absorbed by the buds and inhibit bud elongation. Although glyphosate applied directly to crown buds did not significantly reduce bud elongation, the data does suggest that some glyphosate absorption had occurred. The long term effect of a fall application of picloram at 0.5 and 1.0 lb ai/acre resulted in significant reductions in leafy spurge above-ground cover in the two years following treatment. Glyphosate applied in the fall at 1.0 lb ai/acre resulted in a significant increase in leafy spurge above-ground cover by the following summer. Burning in the spring subsequent to the fall herbicide applications did not increase leafy spurge control. A late season application of picloram is thus more effective than glyphosate at controlling leafy spurge apparently due to its ability to persist in soil and directly target the crown buds.

Introduction

It is the below-ground portions of leafy spurge (*Euphorbia esula* L.) that have contributed so greatly to its reproduction and persistence as a weed. A crown, which is the vertical underground portion of the shoot, develops at the base of stems and forms shoot buds (Best *et al.* 1980, Messersmith *et al.* 1985). The root system is heterorhizic consisting of two types of roots; long roots and short roots (Raju *et al.* 1963). Long roots have extensive apical growth and cambial activity, grow both vertically and horizontally, and produce shoot buds whereas short

roots are short-lived, lack cambial activity, and do not produce shoot buds (Raju *et al.* 1963). The extensive crown and root system, with its thick and corky bark (Coupland and Alex 1954, Bakshi and Coupland 1959, Best *et al.* 1980, Messersmith *et al.* 1985), and abundance of stored food (Bakke *et al.* 1936), overwinters and produces the new shoots in the spring (Best *et al.* 1980).

Most flowering shoots arise from buds located on the crown (Raju 1985). The shoots arising from buds located on the roots are usually from those buds which are in the upper 30 cm of the soil profile (Raju *et al.* 1964) and near the outer edges of a patch (Best *et al.* 1980). Although preformed shoot buds are more abundant on roots near the soil surface (Coupland and Alex 1955, Raju *et al.* 1964), upon disturbance, roots at great depths have the potential to regenerate the whole plant by stimulating the growth and formation of new buds (Coupland *et al.* 1955, Raju *et al.* 1964). The new shoots derived from root buds develop their own crown of shoot buds at the end of the growing season and continue to remain connected with the parent plant for an undetermined length of time (Best *et al.* 1980). The developmentally arrested crown and root buds which do not sprout in the spring are apparently sloughed off during the season and replaced by new buds which begin to appear around flowering time (Monson and Davis 1964).

The ability of root and crown buds to produce shoots is influenced by phenological stage (Raju *et al.* 1964, Dosland 1969, Nissen and Foley 1987a). Raju *et al.* (1964) reported that the regenerative capacity of root fragments during the growing season was lowest in June when flowering was at its maximum. Nissen and Foley (1987) also found root bud elongation to be significantly lower during full flower and greatest during late summer regrowth. No fall dormancy was present in the root buds. In contrast, Dosland (1969) found a dormancy period in crown buds beginning in late August, reaching maximum dormancy in November, and complete release by December. Crown bud activity apparently follows a different pattern than root buds. Although Monson and Davis (1964) found no indication of bud dormancy as measured by shoot emergence, the shoots that emerged in late summer and fall failed to grow to normal heights. It was unclear as to whether their buds were from roots or crown. Dosland (1969) had also observed dwarfed shoots arising from dormant crown buds.

The physiological processes involved in the developmental arrest of crown and root buds are not well understood and yet this information could provide important insights to aid in leafy spurge control (Nissen and Foley 1987a). Nissen and Foley (1987a) determined that root buds were quiescent during most of the growing season due to dormancy enforced by the main shoot (correlative inhibition) rather than dormancy within the bud (innate dormancy). It was only those root buds from fully flowering plants that exhibited innate dormancy. Their data suggests the involvement of shoot-produced indole-3-acetic acid (IAA) in the correlative control of root bud growth. Further work by Nissen and Foley (1987b) found that the endogenous unconjugated

(free) IAA levels were related to phenological stage and were highest in buds which were innately dormant. In contrast, recent work by Metzger (1993) found the IAA levels in root buds initiating growth eight days after shoot removal was 12 times higher than at time zero. Their data suggests that the flow of assimilates from the shoots to the roots suppresses root bud growth. It has also been shown that competition between the root buds and shoots for nitrogen (McIntyre 1972) and water (McIntyre 1979) are significant factors in the mechanism of root bud inhibition. Additionally, McIntyre (1979) suggests bud aeration to possibly be important in affecting bud release. Galitz (1993) found a phytochrome system present in the crown buds of leafy spurge in the fall and suggests its involvement in the regulation of crown bud emergence.

If a means could be developed to manipulate shoot growth from the dormant buds, long-term control could be achieved (Maxwell *et al.* 1987). Although the literature is replete with information on the effects of various herbicide treatments on leafy spurge, few studies looked specifically at the herbicide affects to the below-ground portions of the plant. Maxwell *et al.* (1987) found that glyphosate [*N*-(phosphonomethyl)glycine] translocation to the crown buds was relatively highest at the senescence stage (late August to early September). It is at this time that crown buds are actively elongating toward the soil surface and therefore becoming sinks for glyphosate accumulation (Maxwell *et al.* 1987). After reaching sublethal levels, fall applied glyphosate facilitated prolific shoot bud growth on the crown and upper portions of the root system from the previously inhibited buds. Thus glyphosate could alter the bud dormancy regulation system (Maxwell *et al.* 1987). The greatest translocation of picloram (4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid) to roots occurs during the true-flower and seed-set growth stages (late June) which coincides with the time when picloram applications are most effective (Lym and Messersmith 1991). Picloram did not move with photosynthates to the roots in the fall as hypothesized (Lym and Messersmith 1991). Hunter and McIntyre (1974) found that translocation of 2,4-D [(2,4-dichlorophenoxy)acetic acid] out of the leaves and into the shoot, root, and root buds of leafy spurge was significantly increased by treatments which promoted bud growth.

The present study was designed to investigate the phenology of leafy spurge crown bud elongation; determine if picloram and glyphosate could be directly absorbed by crown buds; and evaluate the effects of a late season herbicide application of picloram and glyphosate on the elongation of crown buds and the recovery of leafy spurge in the field.

Materials and Methods

Study Site

The study site is located in an established leafy spurge field at the maintenance facility of the Minnesota Valley National Wildlife Refuge, 5981 E. Highway 101, Shakopee, Minnesota. The site is located in the floodplain of the Minnesota River. The soil is classified as a coarse sand to loamy coarse sand. The vegetation consists of *Euphorbia esula* L. as the dominant species with *Amaranthus retroflexus* L., *Chenopodium album* L., *Mollugo verticillata* L., *Oenothera biennis* L., *Physalis heterophylla* Nees., *Grindelia squarrosa* (Pursh) Dunal., *Verbena stricta* Vent., *Erigeron strigosus* Muhl., *Polygonum pennsylvanicum* L., *Berteroa incana* (L.) DC., *Solanum rostratum* Dunal., *Conyza canadensis* (L.) Cronq., and *Artemisia ludoviciana* Nutt. also occurring. Nomenclature follows Gleason and Cronquist (1963). Voucher specimens have been deposited in the University of Minnesota herbarium.

Preliminary Crown Bud Measurements

A preliminary experiment was designed to measure crown bud elongation and determine if the relative location of buds on the crown could explain the differential elongation of crown buds after release from inhibition. Four leafy spurge crowns were collected from the field on October 15, 1990 in the right-of-way at the northwest corner of the intersection of Interstate 494 and 5 in Eden Prairie, MN. Crowns were transported to the laboratory where they were rinsed with water and stored in enclosed trays containing moist sphagnum in a refrigerated chamber at 2°C. On November 12, 1990, the crowns were removed from storage, the position of the buds were recorded, and the length of each bud was measured in mm using a 6 inch dial caliper. Crown #'s 1, 3, and 4 each had 10 buds monitored while crown #2 had 8. The crowns were potted in vermiculite, watered, and placed in controlled environment chambers at LD 12:12 (12 hrs light span followed by 12 hrs dark span), temperature 25°C:21°C (25°C during the light span and 21°C during the dark span). The crowns were removed from their pots, the individual buds remeasured, and the crowns repotted daily for approximately three weeks. The crowns were watered as needed. The data is presented for individual buds.

Crown Bud Phenology

Crown Excavation

To determine if crown buds are still actively elongating late in the season, an excavation experiment was performed at the Minnesota Valley National Wildlife Refuge site beginning October 1, 1991. Four leafy spurge crowns were excavated from the west side of a dirt road ("west bank", crown #'s 1-4) and two crowns from the east side ("east bank", crown #'s 5 and 6). The east bank was approximately three feet high and was shaded by the morning sun. The west

bank was at about road level and received full sunlight throughout the day. The soil was carefully removed using a small garden shovel and a 1.5 inch wide painter's brush to expose the crown. Individual crown buds greater than 5 mm in length were labeled using colored embroidery floss loosely tied around the bud. Crown #'s 1, 2, and 4 each had a sample size of five buds. Crown #'s 3 and 6 had a sample size of 2 and 4 buds, respectively. The bud length was measured in mm using a 6 inch dial caliper. The crowns were covered first with vermiculite followed by a top layer of the original soil. The individual plants were marked using a labeled flag. The crowns were re-excavated weekly for measurement and then covered. The experiment was prematurely terminated due to a 28" snowfall on October 31. The change in bud length after 4 weeks was calculated for each individual bud and then averaged for each crown. Bud length measurements are presented graphically for individual buds.

Crown Harvesting Throughout The Growing Season

An additional experiment commenced during the spring of 1993, as a follow-up to the crown excavation experiment, to study the phenology of leafy spurge crown bud elongation. Within a 24.0 m x 9.5 m area located in a leafy spurge infestation at the Minnesota Valley National Wildlife Refuge, 15 randomly numbered flags were placed near large clumps of young leafy spurge shoots on April 24, 1993. The study plot was located along the base of a south facing embankment. Every two weeks starting in early spring and continuing until late fall of 1993, crowns located nearest to the numbered flag were harvested from the field. Crowns were collected from Flag #'s 1-15 on April 24, May 8, May 22, June 5, June 20, July 5, July 17, August 1, August 15, August 28, September 12, September 23, October 9, October 22, and November 6, respectively, with a sample size of 13, 12, 18, 16, 14, 22, 17, 18, 20, 20, 22, 23, 20, 23, and 21 crowns, respectively. Harvested crowns were placed in a plastic bag and transported to the laboratory where they were rinsed with tap water to remove soil debris. The lengths of the first five live buds (starting from the top of the crowns) were measured in mm using a dial caliper. The length, number, and lifestage of shoots as well as observations on bud color and location were also recorded.

Crown Bud Elongation of Herbicide Treated Plants

To evaluate the effects of a late season herbicide application on the elongation of leafy spurge crown buds, picloram and glyphosate were applied to leafy spurge in the field on October 2, 1991 at the Minnesota Valley National Wildlife Refuge. Three 4m² plots were located both in an area with sandy soil ("sandy site") and in an area with loamy soil ("loamy site"). The treatments consisted of picloram (Tordon) at 1 lb ai/acre, glyphosate (Ortho Kleenup) at 1 lb ai/acre, and a control having no herbicide applied. The herbicides were applied using a backpack

sprayer. Crowns were collected on November 11, 1991 from the sandy site and on November 18, 1991 from the loamy site. To locate the crowns, the soil was turned over within each plot using a shovel and the soil clumps broken. The crowns were shaken to remove most of the soil and placed into plastic bags. At the lab, the old top growth and some of the root system was removed. Crowns from the loamy site had to be rinsed with tap water to remove the soil and make the buds more visible. A subsample of the crowns were subjected to a cold treatment. The cold treated crowns were placed into 10" plastic pots covered with either saturated vermiculite (sandy site crowns) or peat moss (loamy site crowns), wrapped in a plastic garbage bag, and placed into a freezer at a temperature of -10°C for either 5 weeks (sandy site crowns) or 6 weeks (loamy site crowns).

The elongation of buds from both non-cold treated and cold treated crowns from each of the two sites were monitored in separate experiments according to the following procedure. Crown buds were marked at the base using a permanent marker to serve as a reference point for measuring bud length since the base of the bud was not always well-defined. The buds were labeled using colored embroidery floss loosely tied around the bud and the length measured in mm using a 6 inch dial caliper. Five crowns from each treatment at each site were potted into 6" plastic pots lined with paper towelling and filled with vermiculite. Due to the lack of crowns with buds from the picloram treatment at the sandy site, only 3 crowns were used in the non-cold treated crowns and no crowns were available for the cold treated experiments. The number of labelled buds per crown varied. Approximately one inch of potting soil was then placed on top (non-cold treated experiments only). The pots were placed into a controlled environment chamber at LD 16:8 Temperature 22°C:12°C. The plants were watered with tap water as needed. After 2 and 4 weeks, the crowns were removed from the pots, bud length remeasured, and crowns repotted and placed back into the controlled environment chamber. The total change in bud length after 2 and 4 weeks was calculated for each individual bud and then averaged for each treatment. Bud growth was considered to be 0 if the bud broke completely off during the two week time interval between measurements. Analysis of variance and Fisher's Protected Least Significant Difference (PLSD) multiple comparison tests were performed using StatView SE+ Graphics software package (Abacus Concepts, Inc).

Crown Bud Elongation of Herbicide Treated Crown Buds

An experiment was performed to determine if picloram and glyphosate applied directly on the crown buds could be absorbed through the bud scales and inhibit bud elongation. Leafy spurge crowns were collected from the field on November 13, 1992 from the Minnesota Valley National Wildlife Refuge site. At the laboratory, the crowns were cleaned in cold water to remove the soil. The cleaned crowns were then layered between wet newspaper in flats. The

flats were placed in plastic bags and stored at -10 °C for one month and then transferred to 4 °C for approximately six weeks.

At the start of the experiment, all but one bud was excised off each of 32 crowns using a razor blade. This was done so that the experimental herbicide treatment effects would not be masked by the dominance effect of buds on the crowns. The length of the bud on each crown was measured using a 6 inch dial caliper. The treatments consisted of picloram (Tordon) at a "high" rate (approximately 1 lb ai/acre-0.52 mls Tordon/50 mls H₂O) and a "low" rate (approximately 0.5 lb ai/acre-0.26 mls Tordon/50 mls H₂O) and glyphosate (Ortho Kleenup - 5 % isopropylamine salt of glyphosate) at a "high" commercial rate (8 fl oz Kleenup/1 gal H₂O) and a "low" commercial rate (8 fl oz Kleenup/1.5 gal H₂O) brushed onto the entire surface of the crown buds using a standard size artist's paintbrush (2 brush dips in appropriate herbicide solution per bud). The control treatment received 2 brush dips of distilled H₂O applied to the bud surface. Crowns were potted in 4 inch plastic pots filled with vermiculite saturated with distilled H₂O. Additional treatments consisted of either picloram or glyphosate at the "high" rate sprayed onto the vermiculite surface of potted crowns using small plastic spray bottles. Each experimental herbicide treatment had 4 replicates while the H₂O control contained 8. Pots were placed in a controlled environment chamber at a setting of LD 16:8, temperature 22°C:12°C. Light intensity was 95 $\mu\text{Em}^{-2}\text{s}^{-1}$ photosynthetic photon flux. Pots were watered as needed. At various times during the monitoring period the crowns were removed from the pots, bud length remeasured, and crowns repotted and placed back into the controlled environment chamber. The total change in bud length was calculated after each sampling period and averaged per treatment. Analysis of variance and Fisher's Protected Least Significant Difference (PLSD) multiple comparison tests were performed on the 7, 15, and 31 day data sets using StatView SE+ Graphics software package (Abacus Concepts, Inc).

In order to quantify the levels of picloram absorbed by leafy spurge crown buds, a second experiment was performed using ¹⁴C labelled picloram. Leafy spurge crowns were collected on October 19, 1993, from the Minnesota Valley National Wildlife Refuge in Shakopee, MN. The crowns were collected from a large, isolated leafy spurge patch and thus suspected to all be genetically identical. Shoots were cut back to 1 to 2 inches above the crown, layered between water-saturated vermiculite in plastic tubs enclosed within plastic bags, and placed into dark storage at 4°C for 5 months. At the start of the experiment, all but one bud was excised from each of 30 crowns. The initial bud length was measured using a dial caliper. Bud size ranged from 4.2 to 17.8 mm in length at the time of treatment. The picloram was applied to each bud in a 10 μl droplet using a micropipette. The picloram treatment solution contained 79 KBq ml⁻¹ of picloram-2,6-¹⁴C (1029 MBq mmole⁻¹, > 99% radiochemical purity) and ¹²C-picloram to reach a final picloram concentration of 9.2 mM. Each bud thus received 22.3 μg of picloram

which approximates a field application of 0.5 lbs ai acre⁻¹. Picloram-2,6-¹⁴C was solubilized in ethanol resulting in a final ethanol concentration of 11 % (v/v) in each droplet. For the control treatment, 10 µl of a 11 % (v/v) solution of ethanol was applied to each bud. Treated crowns were immediately placed into 4 inch plastic pots with water saturated vermiculite. The pots were each enclosed in a 1 gallon sized clear plastic storage bag. The pots were placed randomly in a controlled environment chamber with a constant temperature of 25°C. Photoperiod was 16 h with a light intensity of 180 µEm⁻²s⁻¹ photosynthetic photon flux. Three crowns from each treatment were harvested after 3, 6, 9, 12, and 15 days. Bud lengths were recorded. For the picloram treatment, the buds were excised, weighed, and rinsed twice in 1 ml of 50 % aqueous methanol to remove unabsorbed picloram. The combined wash was added to 10 ml of a biodegradable scintillation solution (Ecoscint A, National Diagnostics, Atlanta, GA) and subject to liquid-scintillation spectrometry (Beckman LS 7000 Liquid Scintillation System, Beckman Instrument, Inc., Fullerton CA). The bud was dried at 60°C for 3 days, weighed, and combusted in a sample oxidizer (Packard Tri-Carb Sample Oxidizer B306, Packard Instrument Co., Downers Grove, IL) using 5 ml Carbo-Sorb (Packard) as the CO₂ trapping solution and 15 ml of a toluene based scintillation cocktail (Permafluor V, Packard). Radioactivity in the samples was measured by liquid-scintillation spectrometry and the amount of absorbed picloram determined.

Field Cover of Herbicide Treated and Burned Plots

A field experiment was performed at the Minnesota Valley National Wildlife Refuge to monitor the long term effects of a late season herbicide application to leafy spurge under field conditions. Plots were set up within uniformly dense leafy spurge patches. One 4 x 4 randomized block ("Herbicide + Burn") and two 4 x 2 randomized blocks ("Herbicide Plot 1" and "Herbicide Plot 2") consisting of 25 m² plots were established. The treatments consisted of picloram (Tordon) at 1 lb ai/acre, picloram at 0.5 lb ai/acre, glyphosate (Ortho Kleenup) at 1 lb ai/acre, and a control having no herbicide applied. The herbicides were applied on October 2, 1991 using a backpack sprayer. Plots were burned in the "Herbicide + Burn" block on May 19, 1992. The above-ground percent cover of leafy spurge was determined prior to treatments (September 24, 1991) and for two years following the treatments (5-7-92, 7-14-92, 9-1-92, 5-8-93, 7-10-93, 9-1-93). Percent cover estimates of leafy spurge were taken using a 0.5 m diameter circular hoop thrown four times into each plot.

Due to errors in herbicide spraying, one plot in the "Herbicide + Burn" block and two plots in the "Herbicide Plot 2" block were not included in the data analyses. Analysis of variance was performed on the original percentage data and on the data transformed using the arcsin square root transformation as suggested by Sokal and Rohlf (1981). Since the statistical results from the transformed data were similar to the original percentage data, only the analyses performed on the

original percentage data is presented. Analysis of variance were run using StatView SE+ Graphics software package (Abacus Concepts, Inc). Analysis of covariance was tried (MACANOVA, Gary W. Oehlert) using the Fall of 1991 data set as the covariate because of statistically significant differences in spurge cover between the "Herbicide + Burn" block and the two "Herbicide" blocks prior to the burn treatment. This analysis proved unsuccessful in separating the initial block differences from the burn treatment effects. Performing analysis of variance on the change in cover (subtracting the Fall 1991 percent cover values from both the Fall 1992 and 1993 values) did appear to solve the problem of block effects confounded with burning effects.

Analysis of Soil Properties

Soil samples were collected from the field at the Minnesota Valley National Wildlife Refuge on October 2, 1992 in the area just outside the control plot from both the sandy and loamy experimental sites and inside the control plots of the "Herbicide + Burn" and the two "Herbicide" only experimental blocks. Five 10 cm cores were taken for each sample using a 22 mm diameter cork borer. Soil samples were placed in plastic bags and then transferred to paper bags for air drying at the laboratory. The dried soil samples were passed through a 2 mm sieve. Hydrogen ion activity was determined using a Cole-Parmer Series 5986 Chemcadet pH/mV meter with a Ag/AgCl combination pH electrode, according to the method of Wilde *et al.* (1972). Percent nitrogen (Kjeldahl nitrogen without nitrate reduction), extractable phosphate (Bray P-1), total organic carbon (soils without carbonates), and exchangeable Ca, Mg, Na, and K (equilibrium with ammonium acetate) determinations were performed by the University of Minnesota Department of Soil Science Research Analytical Laboratory. Particle size distribution, determined by sedimentation, was conducted by the University of Minnesota Soil Survey Laboratory.

Results

Preliminary Crown Bud Measurements

The results from the preliminary experiment to measure crown bud elongation and test if the relative location of buds on the crown could be a factor in explaining their differential elongation are presented in Figures 3.1 and 3.2. Most buds began to elongate within 3 days. Although almost all buds on each crown elongated during the three week monitoring period, only one bud each from Crown #3 and Crown #4 and four from Crown #2 elongated beyond 20 mm. Crown #2 had the smallest population of buds. Generally, the buds that exhibited the greatest growth, as well as those buds which died, were nearer to the top of the crowns. Initial bud length

did not appear to be an indicator of ultimate length increase. Bud death was usually preceded by a decrease in bud length.

Crown Bud Phenology

The results of the October 1992 field excavation of leafy spurge crowns to determine if the buds are actively elongating at this time are presented in Figures 3.3 and 3.4. Crown #'s 1-6 had mean bud length increases of 5.9, 2.0, 3.1, 2.0, 2.3, and 7.5 mm, respectively, by the end of the four week monitoring period. Many of the marked buds, especially those from crown #'s 1 and 6, had changed from having tightly imbricate pink bud scales to loosely appressed green bud scales. There were no apparent differences in bud activity between crowns from the east bank as verses the west bank.

The results from crown bud measurements taken throughout the entire 1993 growing season are presented in Figure 3.5 and Tables 3.1 and 3.2. A consistent pattern of bud length relative to bud position on the crown throughout the monitoring period was not observed (Figure 3.5) although analysis of variance of the data combined for all time points did reveal a general trend of decreasing bud length with buds further down on the crown (Table 3.1). Despite the large variation in bud length within as well as between each time point, a general phenological pattern of bud length can be discerned (Figure 3.5). Bud length decreased from time point 1 to a minimum value occurring at time point 4 which coincided with the end of flowering (Table 3.2). After time point 4 there was a gradual increase in bud length with maximum bud lengths occurring at time point 13 which coincided with the beginning of senescence (Table 3.2). Bud activity, as judged by bud color (see Coupland and Alex 1955 for classification), also followed the same pattern (Table 3.2). Crown buds were initially pink but became brown and many died. After time point 4 the brown buds became pink at the tips and new pink buds began to form. By time point 12, the buds were enlarged and pink.

Crown Bud Elongation of Herbicide Treated Plants

The results of the experiment to evaluate the effects of a late season herbicide application on the elongation of leafy spurge crown buds are presented in Figure 3.6, and Table 3.3. Differences in bud elongation between the two plot sites, sandy or loamy, were not statistically significant as determined by analysis of variance ($P < 0.05$, analyses not presented) despite the large differences in soil properties (see Table 3.4). Although bud elongation from crowns receiving a cold treatment were less than the non-cold treated crowns, this difference also was not found to be significant as determined by analysis of variance of the data at $P < 0.05$ (analyses not presented). Since the effects of both the plot site and cold treatment were not statistically significant, the data was combined for plot site and cold treatment. Analysis of variance of the

combined data revealed statistically significant ($P < 0.05$) herbicide treatment effects. Both picloram and glyphosate significantly reduced bud elongation as compared to the controls (Table 3.3). Many of the buds from the picloram treated crowns became brown, shriveled and then broke completely off or died during the monitoring period. Although picloram appeared to be more effective at inhibiting bud growth than glyphosate, the differences in mean bud elongation between the picloram and glyphosate treatments were not statistically significant.

Crown Bud Elongation of Herbicide Treated Crown Buds

The results of the experiment to determine if picloram and glyphosate applied directly to the crown buds could be absorbed through the bud scales and inhibit bud elongation are presented in Figure 3.7 and Table 3.5. All picloram treatments reduced the mean bud elongation to below that of the control treatment throughout the monitoring period (Figure 3.7). This reduction was statistically significant for the picloram-high treatment at 7, 15, and 31 days, and the picloram-spray and picloram-low treatments at 15 days (Table 3.5). Although no statistically significant differences in bud elongation occurred between the glyphosate treatments and the controls, there was a large increase in mean bud elongation in the glyphosate-low treatment to values greater than the control after 15 days. Statistically significant bud elongation differences did occur between both the spray and low glyphosate treatments with the picloram-high and the picloram-low treatment (Table 3.5).

The results of the experiment using ^{14}C picloram applied directly to crown buds of leafy spurge at a rate approximating $0.5 \text{ lbs ai acre}^{-1}$ similarly reduced the mean bud elongation to values significantly below that of the control treatment throughout the monitoring period (compare Figure 3.8 to Figure 3.7). The amount of picloram present within the treated buds at time of harvest ranged from 2 to 9 % of the $22.3 \mu\text{g}$ picloram applied to each bud (Figure 3.9). Regression analysis of the amount of absorbed picloram with bud dry weight revealed a statistically significant positive slope indicating that the larger buds absorbed more of the applied picloram (Figure 3.10). The average amount of picloram present in the bud wash was $0.135 \mu\text{g} \pm 0.023$ (SEM) which represents about 0.6 % of the total picloram applied.

Field Cover of Herbicide Treated and Burned Plots

The results of the field experiment designed to monitor the effects of a late season herbicide application to leafy spurge followed by a burn are presented in Tables 3.6 and 3.7. In the herbicide only treated plots (Table 3.6), picloram at both rates caused significant reductions in leafy spurge cover in comparison to both the glyphosate and control treatments throughout the entire two year monitoring period. Glyphosate resulted in a significant reduction in leafy spurge cover during only the first spring following treatment (May 1992). By July of 1992, leafy spurge

cover in the glyphosate treated plots increased to values significantly greater than the controls, thereafter levelling off to values similar to the control treatment. The results in the herbicide + burn plots (Table 3.7) were similar for picloram. The glyphosate treatment in the herbicide + burn plots never resulted in cover values significantly lower than the controls but did result in values significantly greater than the controls in September of 1992 and May of 1993 (Table 3.7).

To eliminate initial differences in leafy spurge cover between the burned and unburned plots, a two factor analysis of variance of the fall change in cover data (September '92 minus September '91, and September '93 minus September '91) was performed. The spring burn treatment was not found to be statistically significant ($P < 0.05$, analyses not presented).

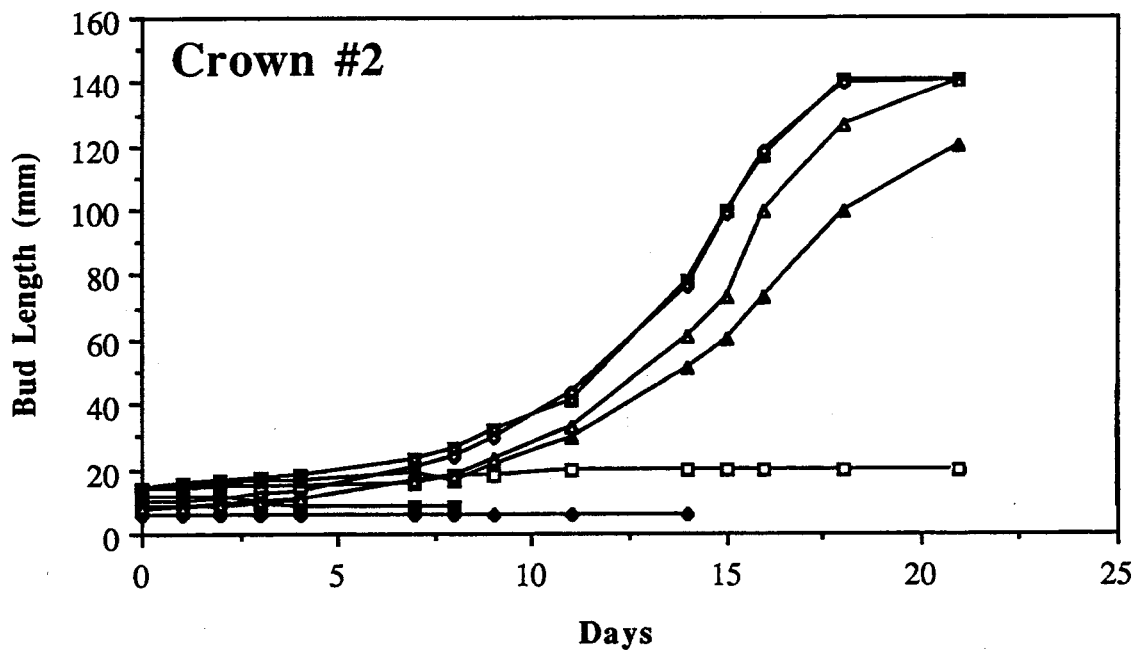
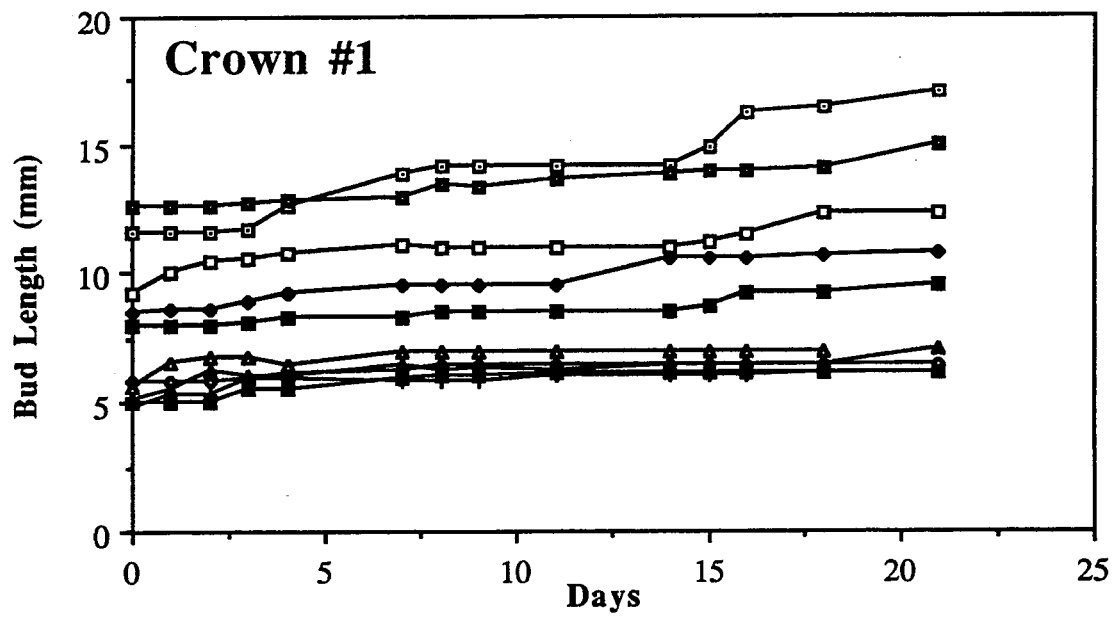


Figure 3.1. Elongation of individual leafy spruce crown buds from Crowns #1 and #2 in the preliminary crown bud experiment.

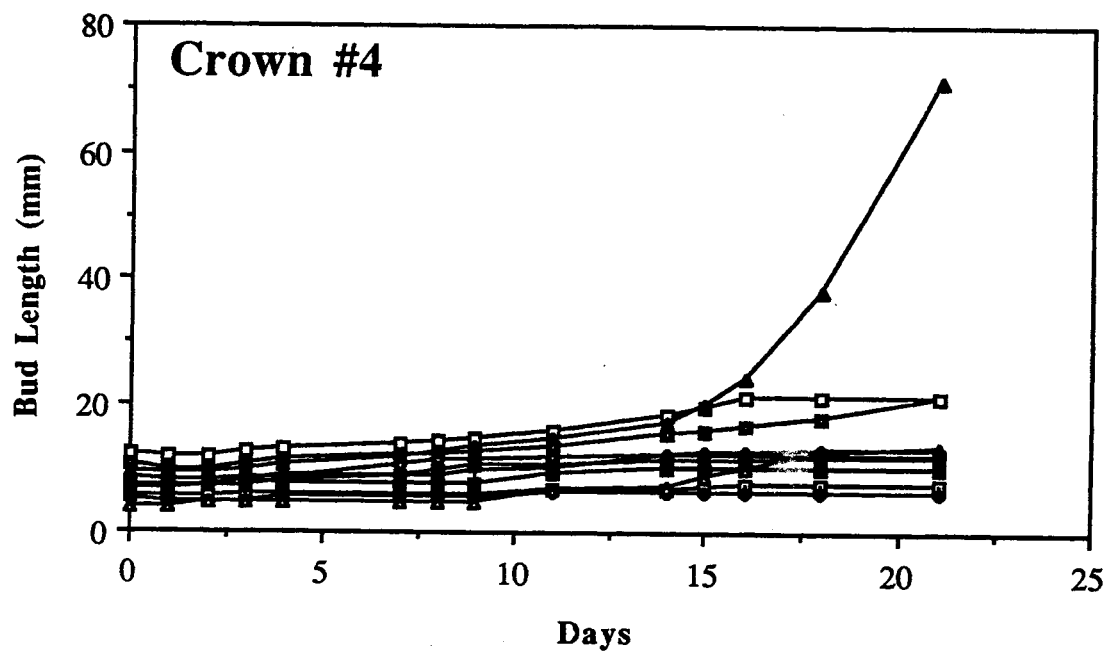
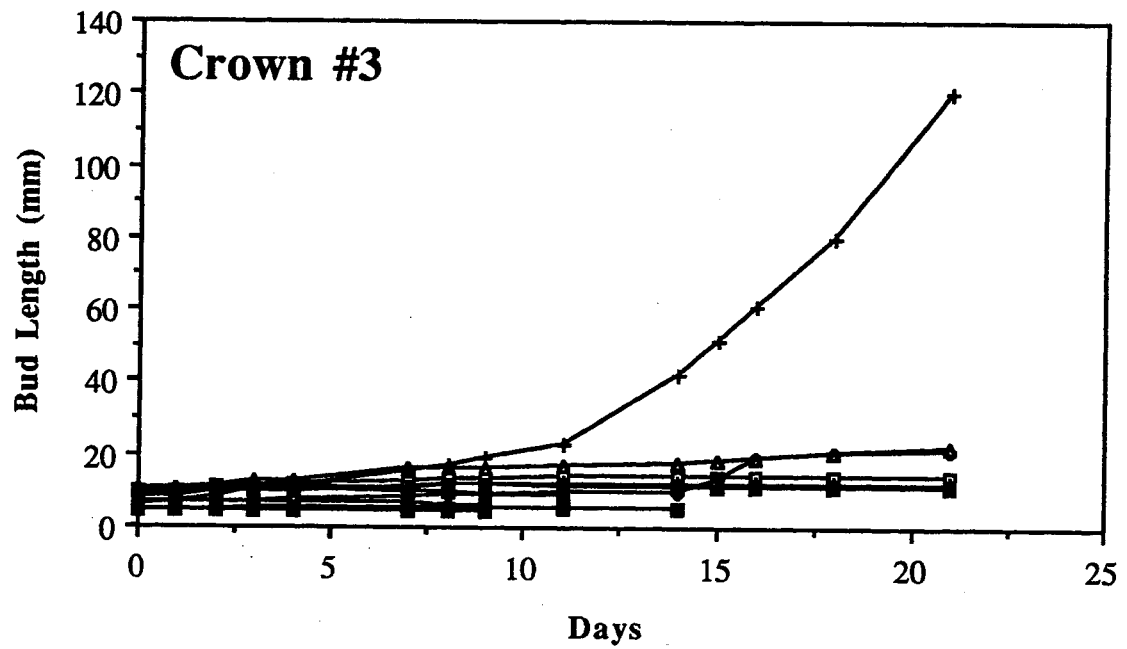


Figure 3.2. Elongation of individual leafy spurge crown buds from Crowns #3 and #4 in the preliminary crown bud experiment.

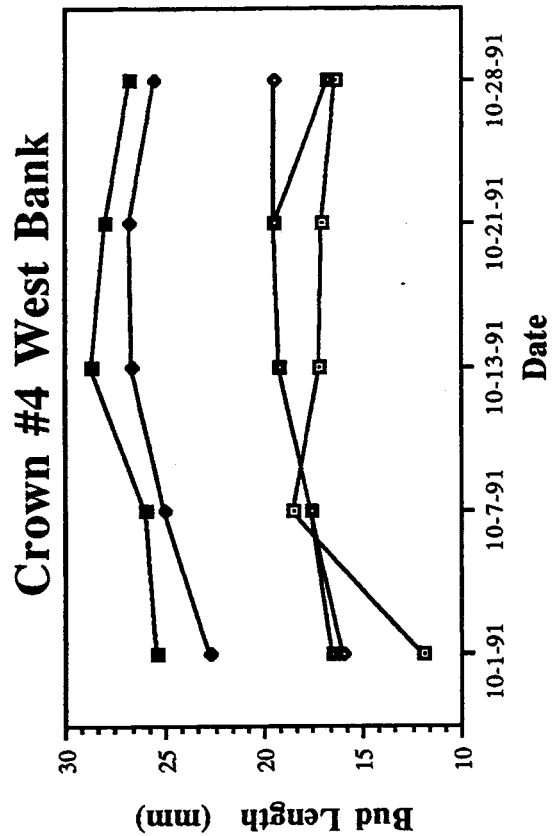
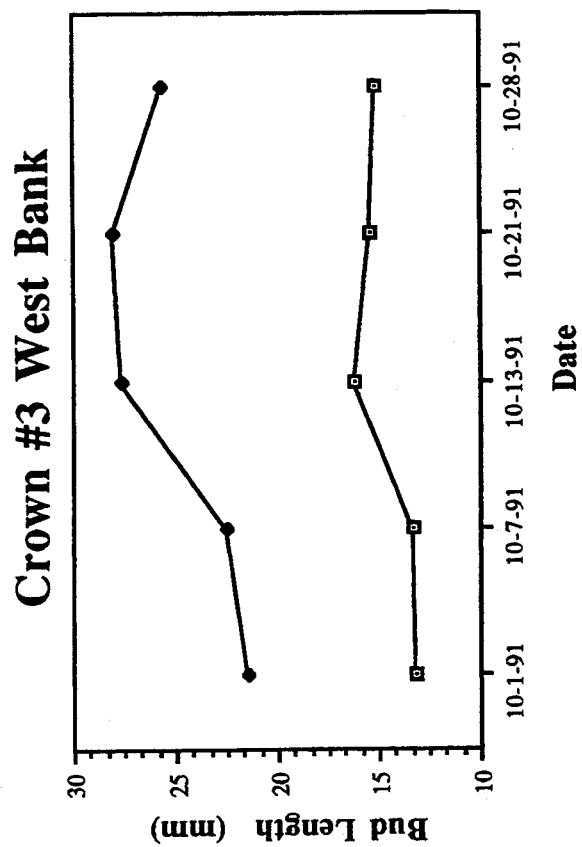
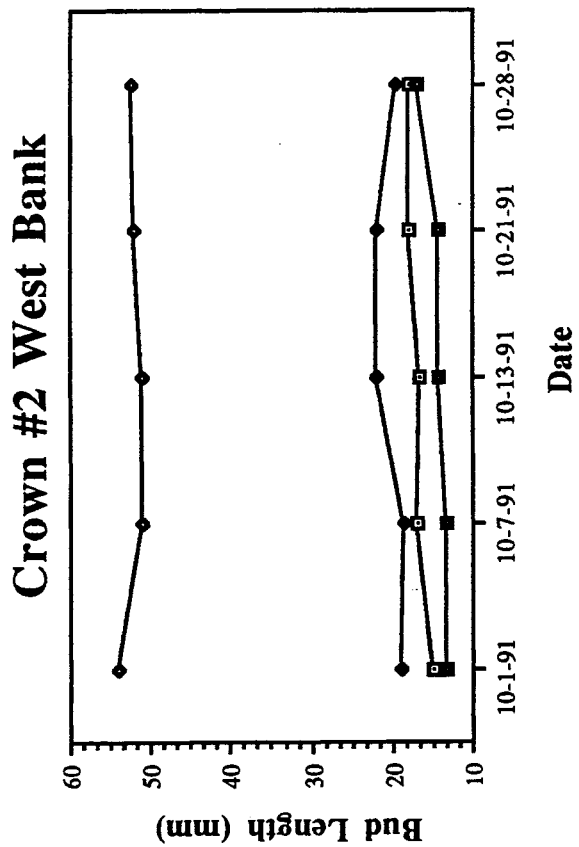
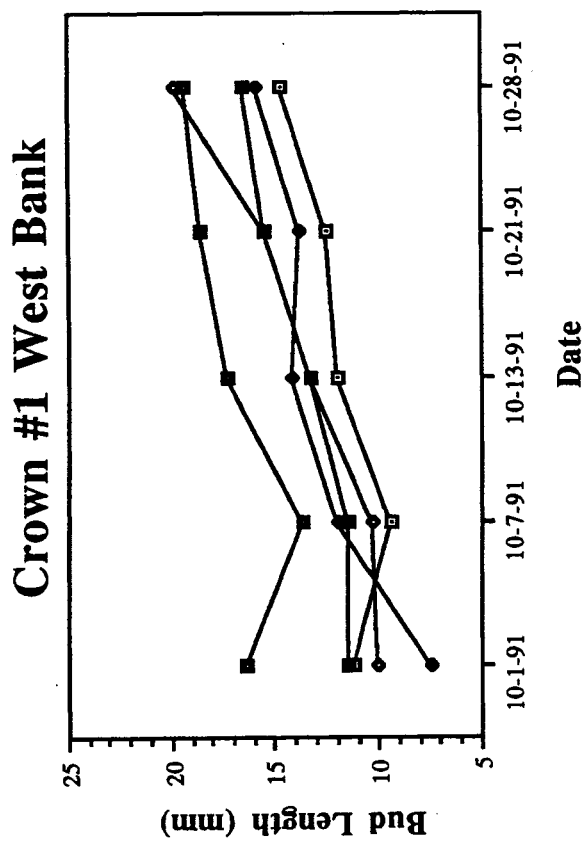


Figure 3.3. Bud elongation from excavated leafy spruce crowns from the west bank.

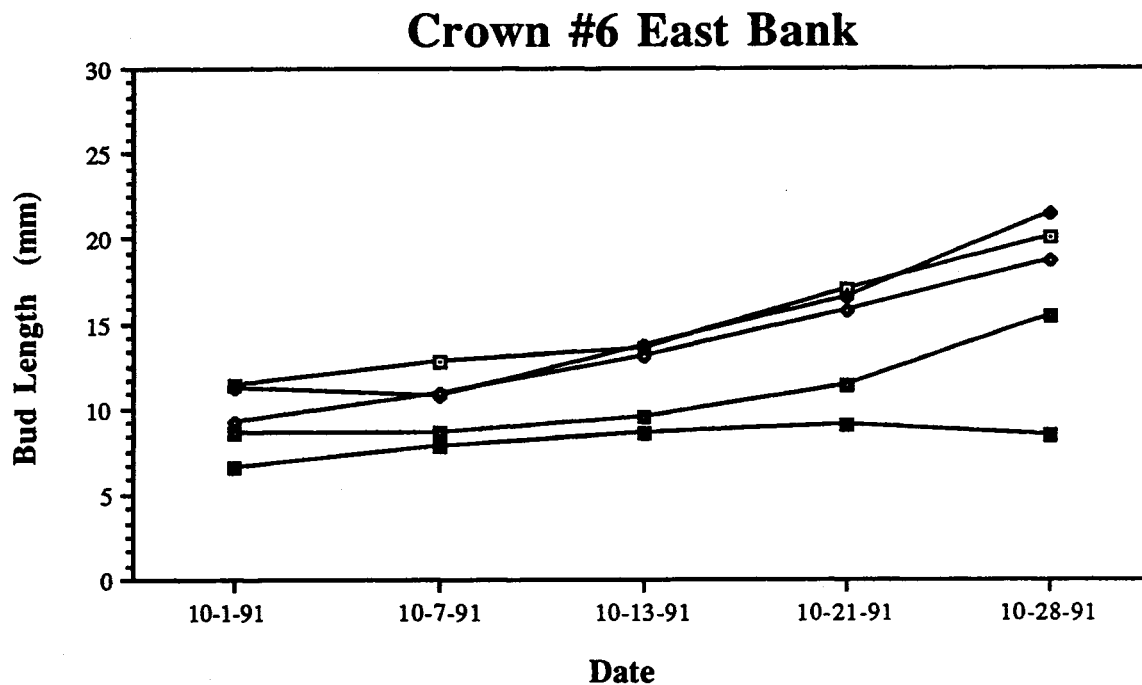
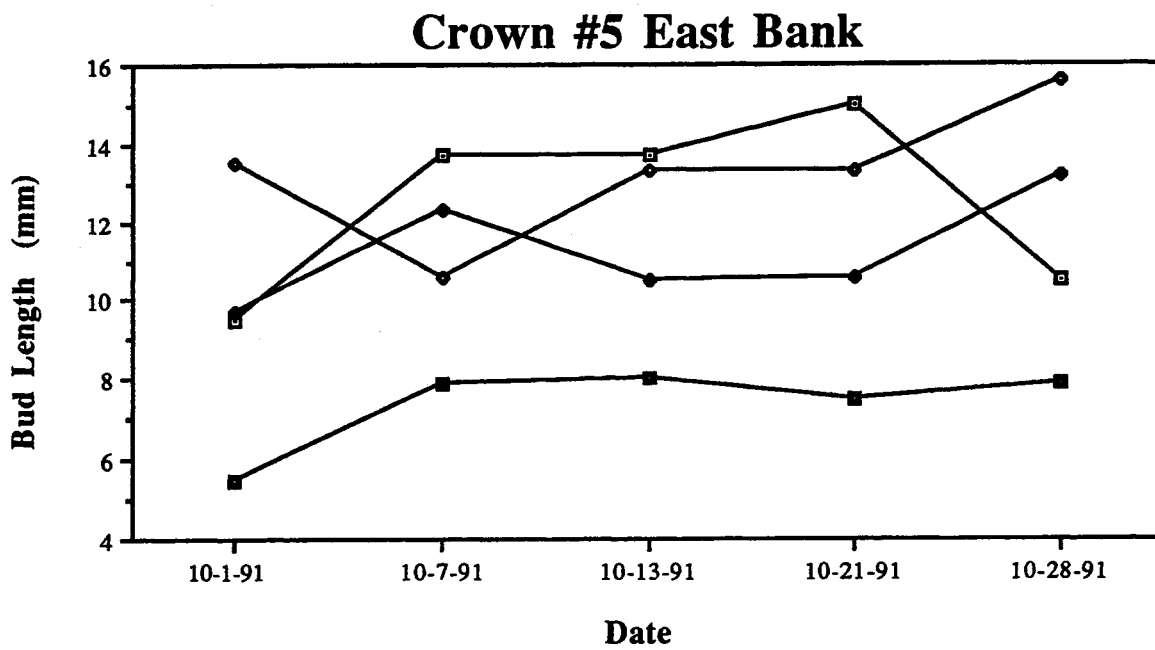


Figure 3.4. Bud elongation from excavated leafy surge crowns from the east bank.

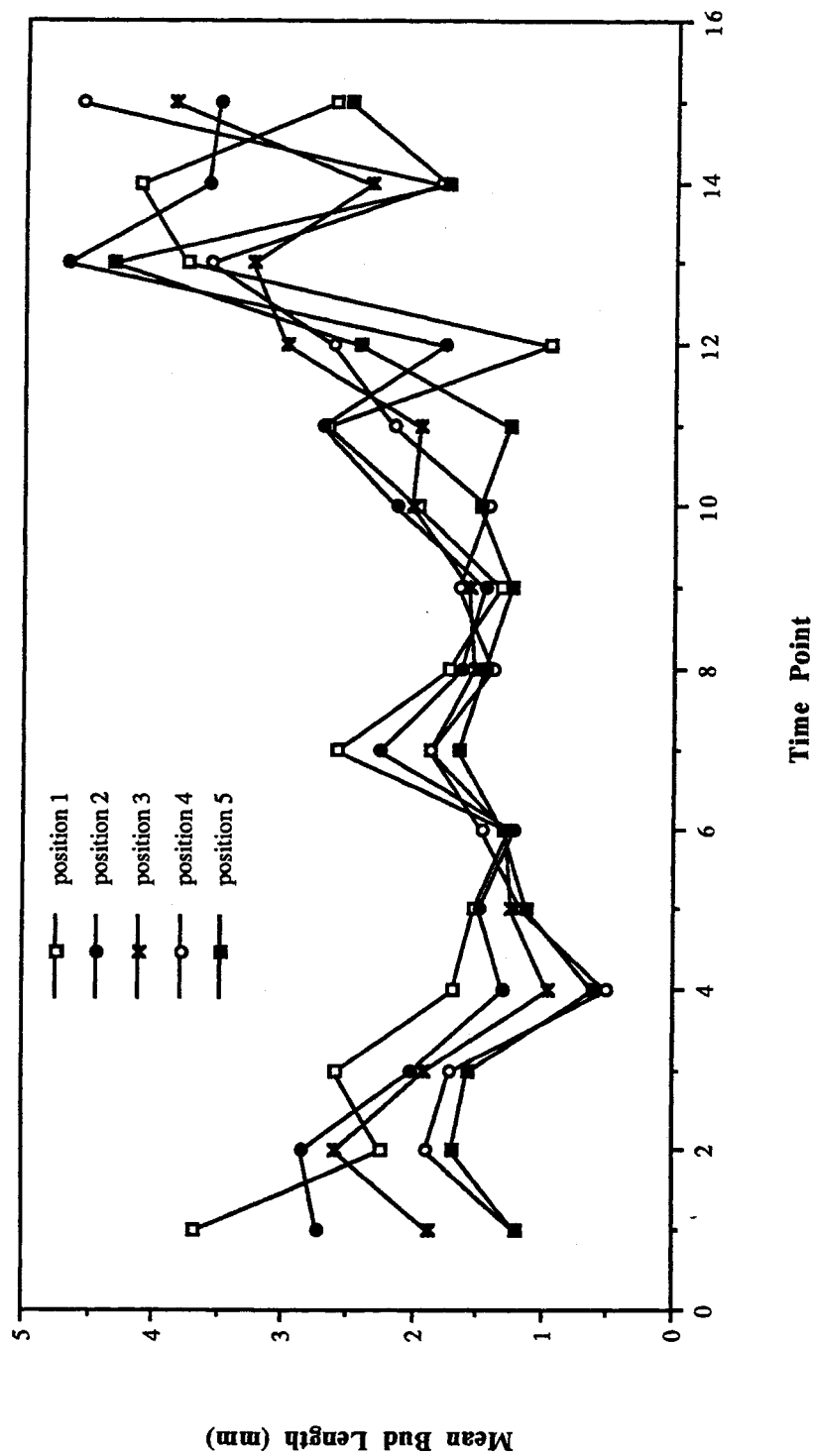


Figure 3.5. Bud lengths of first five buds on leafy spurge crowns during the 1993 growing season. Time points 1 through 15 refer to dates April 24, May 8, May 22, June 5, June 20, July 5, July 17, August 1, August 15, August 28, September 12, September 23, October 9, October 22, and November 6, respectively.

Table 3.1. Comparison of mean bud lengths of the first five crown buds of leafy spurge measured during the 1993 growing season.

Crown Bud Position	Mean Bud Length (mm)
Position 1	2.31 ab
Position 2	2.37 a
Position 3	2.13 ab
Position 4	2.01 bc
Position 5	1.75 c

**Means within a column followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Table 3.2. Observations in leafy spurge crown bud phenology during the 1993 growing season.

Time Point	Date	Life Stage	Shoot Height (inches)	Bud Observations
1	Apr. 24	shoot expansion	3-6	Crown buds mostly located below expanded shoot.
2	May 8	flower bud	12-18	Buds dead near expanded shoot.
3	May 22	flowering	18-24	Buds brown, dying. Live buds further down on crown.
4	June 5	flowering	8-12	Buds brown, scarce.
5	June 20	immature seed	14-22	Buds small, brown, some pink at tips.
6	July 5	immature & mature seed	18-24	New pink buds on base of current years' shoot.
7	July 17	seed dispersal	16-30	Buds mostly not pink, not located on base of current years' shoot.
8	Aug. 1	post-seed dispersal	16-20	Some buds pink. Some crowns with buds on shoot base.
9	Aug. 15	post-seed dispersal	8-28	Brown buds getting new pink growth at tips. New pink buds present, usually at base of shoot.
10	Aug. 28	post-seed dispersal	20-30	Buds mostly pink. Brown buds becoming pink at tips.
11	Sept. 12	post-seed dispersal	14-24	Buds mostly pink.
12	Sept. 23	post-seed dispersal	14-30	Buds enlarged, pink, and fleshy.
13	Oct. 9	post-seed dispersal	18-28	Some crowns with numerous small buds at base of shoot and with large buds further down.
14	Oct. 22	senescence	16-20	Buds pink, enlarged.
15	Nov. 6	2" snowfall shoots broken		Buds pink, enlarged.

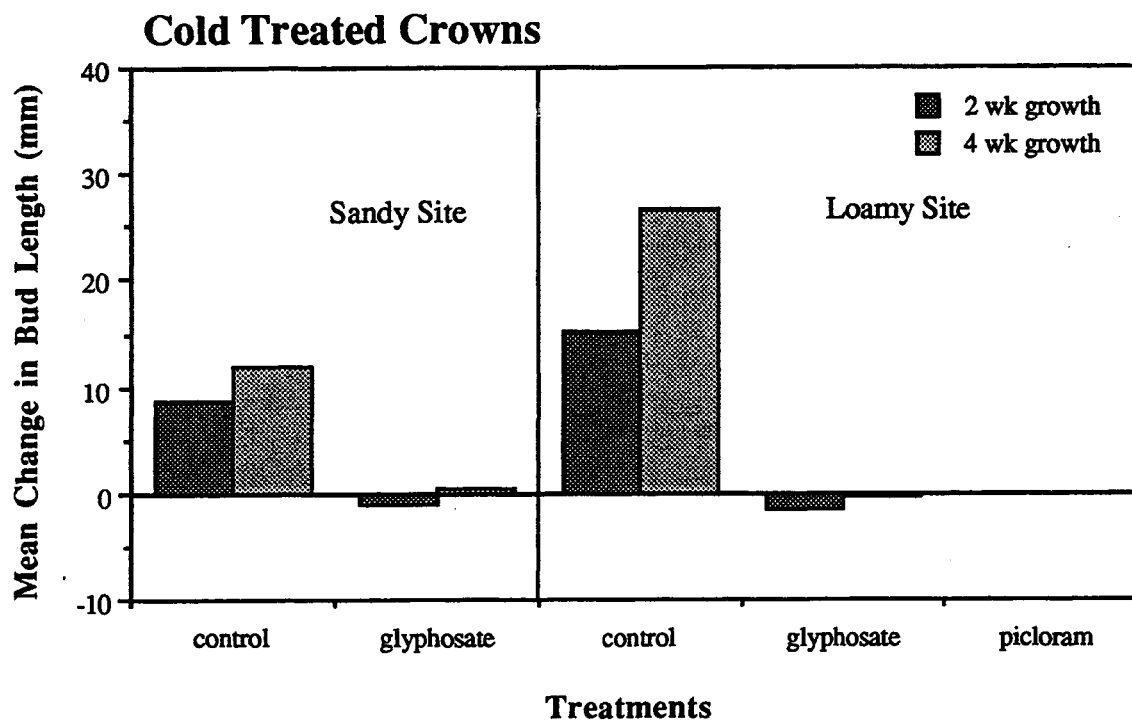
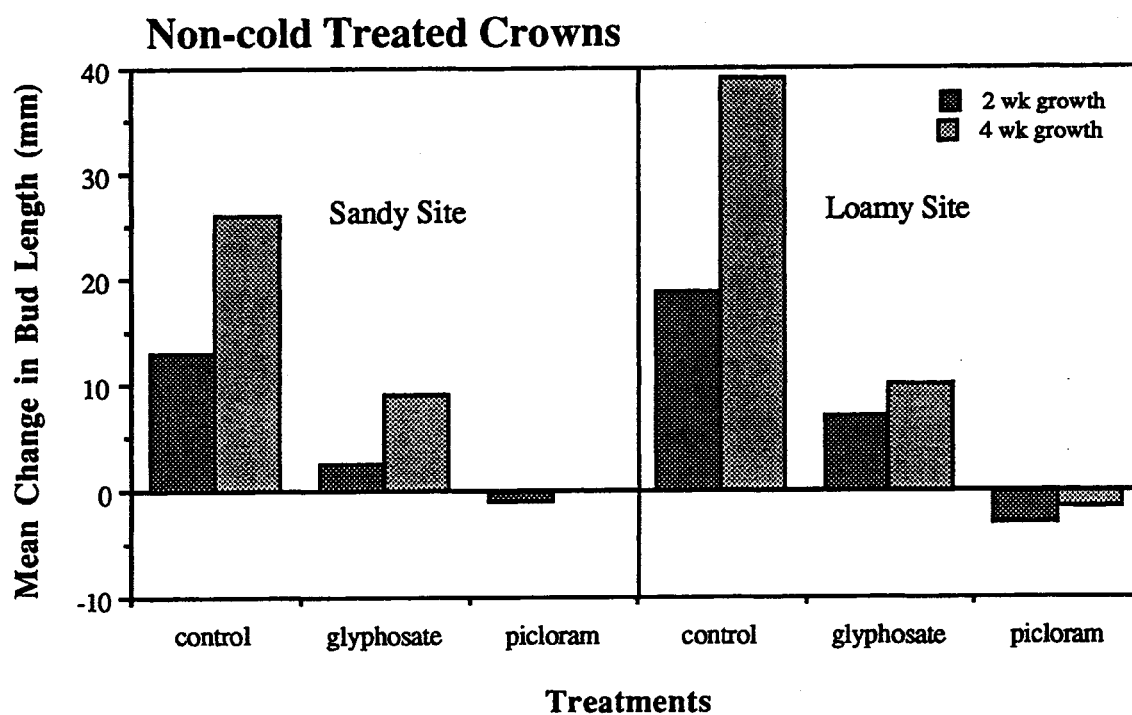


Figure 3.6. Comparisons of crown bud elongation among herbicide treated leafy spurge plants from non-cold treated and cold treated crowns.

Table 3.3. Mean change in crown bud length of harvested leafy spurge plants treated in the field with the herbicides glyphosate and picloram.

Treatment	Mean change in bud length (mm)*	
	2 weeks	4 weeks
control	14.0 a**	25.9 a
glyphosate (1 lb/acre)	2.8 b	5.7 b
picloram (1 lb/acre)	-1.4 b	-0.7 b

*Data combined for plot site and cold treatment.

**Means within a column followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Table 3.4. Physical and chemical properties of soil samples collected from the field plots located at the Minnesota Valley National Wildlife Refuge site.

	Sandy site	Loamy site	Herbicide + Burn	Herbicide Plot 1	Herbicide Plot 2
% N	0.07	0.21	0.08	0.09	0.09
% organic carbon	0.88	2.60	0.80	0.97	0.88
pH	6.43	6.36	6.47	6.38	5.57
P (ppm)	14	30	24	15	12
K (ppm)	59.3	186.4	61.4	73.5	93.9
Ca (ppm)	1002.5	1293.0	768.4	974.3	1044.4
Mg (ppm)	139.2	218.7	152.7	182.4	187.6
Na (ppm)	4.4	5.2	5.6	6.3	3.8
% sand	90	84			
% silt	6	9			
% clay	4	7			

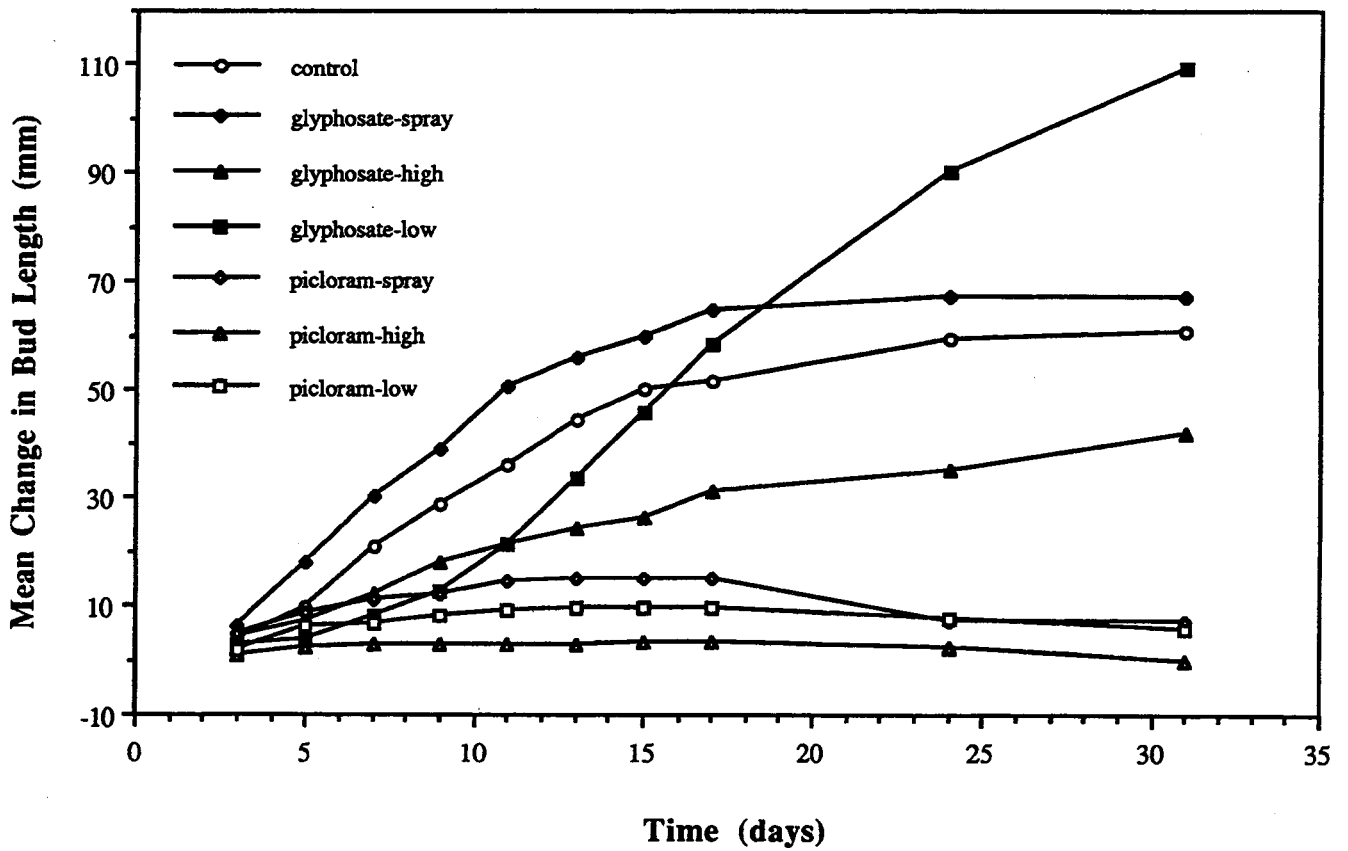


Figure 3.7. The effects of picloram and glyphosate applied directly to crown buds of leafy spurge (see text for explanation of treatments).

Table 3.5. Mean elongation of herbicide treated leafy spurge crown buds after 7, 15, and 31 days.

Herbicide Treatment	Mean Bud Elongation (mm) after 7 Days	Mean Bud Elongation (mm) after 15 Days	Mean Bud Elongation (mm) after 31 Days
control	20.6 ab*	49.9 a	61.0 ab
glyphosate-spray	30.1 a	59.6 a	67.3 ab
glyphosate-low	8.2 bc	45.6 ab	109.1 a
glyphosate-high	11.8 bc	26.0 abc	42.0 bc
picloram-spray	11.1 bc	15.1 bc	7.2 bc
picloram-low	6.6 bc	9.7 c	5.4 bc
picloram-high	2.8 c	3.0 c	-0.3 c

*Means within a column followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

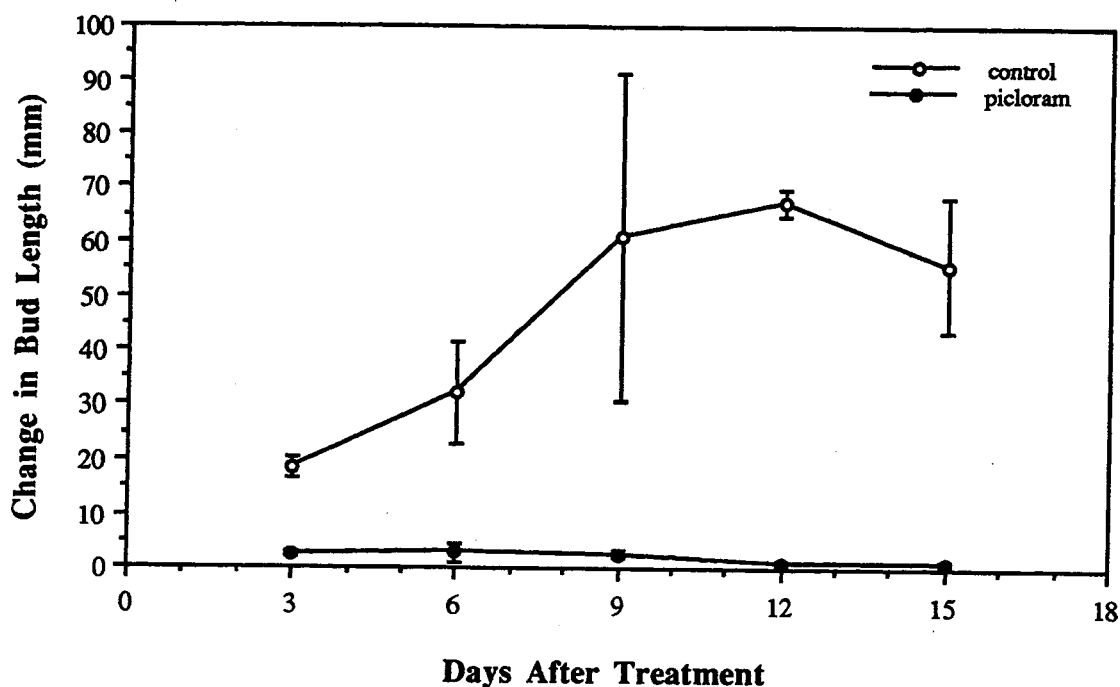


Figure 3.8. Bud elongation effects of ^{14}C labelled picloram applied directly to the crown buds of leafy spurge. Error bars represent SEM.

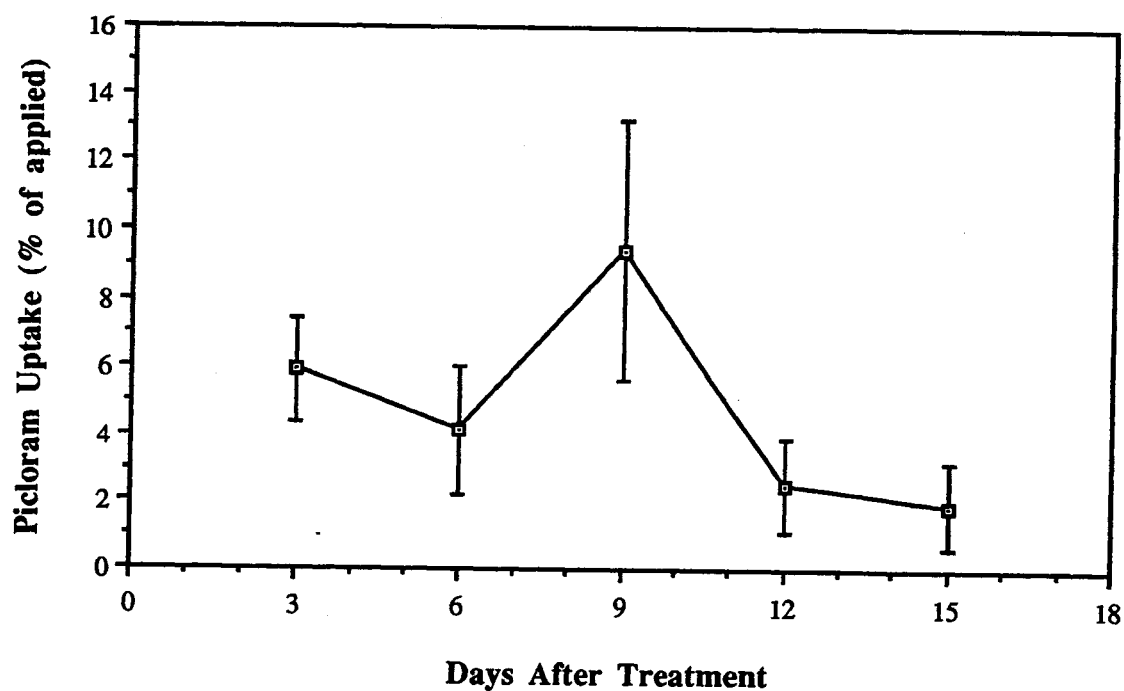


Figure 3.9. The uptake of ^{14}C labelled picloram by crown buds of leafy spurge. Error bars represent SEM.

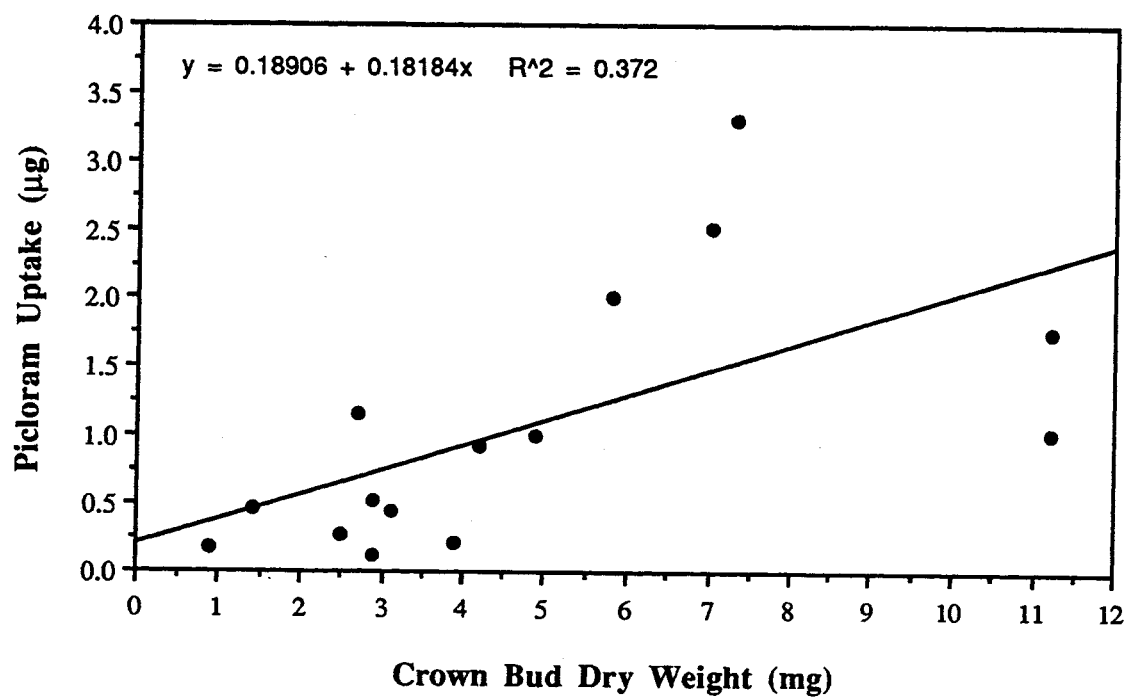


Figure 3.10. The relationship between picloram uptake and dry weight of leafy spurge crown buds. The slope of the regression equation is significantly different from 0 at the 95 % level of significance.

Table 3.6. Field monitoring of leafy spurge percent above-ground cover in herbicide treated plots.

Herbicide Treatment	Mean % cover of leafy spurge						
	Sept. 1991*	May 1992	July 1992	Sept. 1992	May 1993	July 1993	Sept. 1993
control	24.4 a**	20.6 a	37.5 b	29.4 a	21.1 b	41.9 a	31.3 a
glyphosate (1 lb/acre)	19.2 a	6.2 b	65.4 a	32.9 a	35.4 a	45.0 a	27.9 a
picloram (1 lb/acre)	15.0 a	0.0 c	0.3 c	0.0 b	0.8 c	1.4 b	0.6 b
picloram (0.5 lb/acre)	28.3 a	0.0 c	2.1 c	1.8 b	1.3 c	2.8 b	2.1 b

*September 1991 data set represents cover values in plots prior to herbicide application.

**Means within a column followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Table 3.7. Field monitoring of leafy spurge percent above-ground cover in herbicide treated and burned plots.

Herbicide + Burn Treatment	Mean % cover of leafy spurge						
	Sept. 1991*	May 1992	July 1992	Sept. 1992	May 1993	July 1993	Sept. 1993
control	11.3 a**	5.2 a	23.8 a	8.7 b	7.9 b	16.3 a	10.4 a
glyphosate (1 lb/acre)	19.4 a	2.9 ab	30.0 a	15.3 a	13.3 a	20.0 a	11.4 a
picloram (1 lb/acre)	14.5 a	0.4 bc	4.0 b	0.8 c	0.9 c	2.4 b	4.4 b
picloram (0.5 lb/acre)	7.0 a	0.0 c	0.6 b	0.4 c	0.3 c	2.8 b	1.2 b

*September 1991 data set represents cover values in plots prior to herbicide application.

**Means within a column followed by the same letter are not significantly different according to Fisher's PLSD multiple comparison test at a 95 % level of significance.

Discussion

Preliminary Crown Bud Measurements

The pattern of crown bud elongation was variable among the four individual leafy spurge crowns monitored. Crown #'s 3 and 4 reflect strong apical dominance among the enlarging buds with only one shoot emerging per crown while in Crown # 2 the apical dominance was much weaker since four shoots had emerged. Although crown size was not measured in these preliminary experiments, differences in crown size may be an important factor determining the number of shoots a crown can support. Field observations by the authors seem to support this in that the smaller leafy spurge crowns rarely have more than one shoot. Large crowns supporting several shoots would lend support to the concept of internal competition for water and nitrogen affecting root bud inhibition as proposed by McIntyre (1972, 1979) since larger, more vigorous leafy spurge plants would have a well developed root system and thus a better ability for acquiring water and nutrients. The crown buds that would ultimately expand to become shoots could not be predicted from initial bud length. Nissen and Foley (1987a) similarly found no significant relationship between leafy spurge root bud growth and initial root bud size. Crown bud expansion could be predicted to some extent from the relative position of the bud on the crown since most bud activity, whether elongation or death, occurred near to the top of the crown.

Crown Bud Phenology

Knowing when crown buds are most actively elongating is important to appropriately time weed control practices so as to maximize injury to these perennating organs. The crown excavations revealed that generally, crown buds were still actively elongating during the month of October in 1991, although there was a lot of variability among the individual buds. During the monitoring period it was observed that some of the crown buds began to turn green, apparently signifying the onset of shoot expansion which normally occurs in the spring. This response may have resulted from the exposure of the buds to light since studies by Bonnett (1972) have found that root buds initiated on *Convolvulus arvensis* do not elongate unless the roots grow close enough to the surface of the ground to perceive light. Red-light exposures induced bud elongation in *Convolvulus* while far-red light reversed the promotive effect (Bonnett 1972). Recent studies by Galitz (1993) have indicated a phytochrome system present in leafy spurge crown buds in the fall and which may be involved in the prevention of crown bud emergence. In the present study, some of the measured bud elongation may therefore have been due to this premature shoot expansion rather than to actual fall bud growth.

A second bud phenology study was performed which eliminated the effect of light exposure by measuring buds from a unique sample of leafy spurge crowns for each time point. This study

was also performed to determine the pattern of bud growth throughout the entire growing season. Note from Table 3.2 that at no time were any buds green in color. Although sampling a unique set of crowns for each time point eliminated the light exposure effect on buds, it did result in the phenological effects being confounded with the inherent variability among leafy spurge samples. For example, time point 4, which had the lowest mean bud length of the season (Figure 3.5), also had above-ground shoots which were unusually short (Table 3.2). Thus, the low mean bud length values obtained at this time may not reflect a true phenological effect but rather an inherent variation in the leafy spurge sample. The variability among leafy spurge samples can also in part explain the apparent rise in mean bud length during time point 7 (Figure 3.5). Some of the crowns collected at time points 6 and 8 had numerous small buds (<1.0 mm) developing at the base of the current season's shoot which were included in the bud length measurements (Table 3.2). The crowns collected at time point 7 did not have these small buds thus resulting in a greater mean bud length. The variability caused by the presence of some crowns having these small buds could possibly be reduced by having a minimum size limit to buds measured or by measuring the five largest buds on each crown regardless of location.

Despite the variability, a phenological pattern of bud length throughout the 1993 season did emerge. Upon shoot emergence in April, there was a gradual decline in mean bud length caused by the withering and dying of buds until the end of flowering about mid-June. After flowering was complete there was a gradual increase in mean bud elongation with new buds being formed as well as older buds becoming more active. Just prior to senescence in early to mid October, bud length levelled off at a maximum mean value. The same phenological pattern was found for leafy spurge shoot emergence by Monson and Davis (1964) although it is unclear whether crown or root buds were used. Raju *et al.* (1964) found a similar pattern with the regenerative capacity of leafy spurge root fragments in that a minimum value occurred in June, when shoot growth was most vigorous and flowering was at its peak. Nissen and Foley (1987a) also found that excised root buds taken from leafy spurge plants that were fully flowering showed reduced elongation which indicated a period of innate bud dormancy rather than correlative inhibition. It is probable that the underlying mechanism to this phenological pattern may involve the plant growth regulator IAA (indole-3-acetic acid) which is translocated from the shoot (Nissen and Foley 1987a). Further work by Nissen and Foley (1987b) examined the relationship of plant phenology to root bud endogenous IAA levels and found that free IAA levels were highest in leafy spurge root buds during full flower as compared to the vegetative and post flower phenologic stages. Although a study relating plant phenology with IAA levels has not been performed for leafy spurge crown buds, since both root and crown buds seem follow a similar phenological pattern of bud elongation, IAA is also likely to be involved. In the present study, the finding that leafy spurge crown bud growth is a gradual process commencing after flowering is supported by

Monson and Davis (1964) although (Galitz 1993) states that the crown buds begin to elongate in the fall after senescence.

There was a general decrease in bud size from the uppermost bud on the crown (position 1) to the fifth bud (position 5) on the crown (Table 3.1). Although at first this appears to support the previous observation that most bud activity occurred nearer to the top of the crown, our preliminary crown bud measurements and studies by Nissen and Foley (1987a) on root buds indicate a lack of relationship between bud growth and initial bud size.

Crown Bud Elongation of Herbicide Treated Plants

Both picloram and glyphosate applied in the fall to senescing leafy spurge were very effective at inhibiting crown bud elongation. Although the herbicide treated leafy spurge crowns were collected from the field about mid November, a time in which Dosland (1969) found crown buds to be dormant, a late fall dormancy period in leafy spurge crown buds was not evident from our data since crown bud elongation was not significantly different between crowns receiving a cold treatment and crowns not receiving a cold treatment. It is possible that the dormancy may manifest itself in stunted shoot growth rather than reduced bud elongation since Dosland (1969) found various degrees of dwarfing and reduced shoot elongation from dormant leafy spurge buds. Since picloram, unlike glyphosate, is persistent and mobile in the soil, differences in soil properties could result in differences in herbicide availability to leafy spurge. The differences in soil properties between the "loamy" and "sandy" sites did not result in any significant differences in effectiveness of the herbicides on crown bud elongation. It is possible that the effectiveness of picloram at 1 lb/acre is not reduced within this range of soil variation or that crown bud elongation was inhibited via picloram which was mainly foliarly absorbed and subsequently translocated to the crown. Lym and Messersmith (1991) determined that the maximum translocation of picloram to the roots of leafy spurge is during the true-flower growth stage and to a lesser extent during fall regrowth.

Crown Bud Elongation of Herbicide Treated Crown Buds

Picloram, applied directly to leafy spurge crown buds at a rate of 0.5 lb ai/acre, was found to be present within the bud tissues and inhibit bud elongation. The amount of picloram in leafy spurge buds at the time of harvest ranged between 2 and 9 % of the total amount applied. Foliar absorption of picloram is known to vary greatly depending on the relative humidity, temperature before and at the time of application, plant growth stage, solution pH, whether applied alone or with other herbicides, spray additives, as well as the plant species (Sterling and Lownds 1992, Lym and Messersmith 1991, Lym and Messersmith 1990, Lym and Moxness 1989, Moxness and Lymn 1989). The same variation in picloram absorption would thus be expected for crown bud

tissues as well. The total amount of absorbed picloram by leafy spurge crown buds is probably much higher than the levels of picloram measured within the treated buds at the time of harvest due to translocation. Unpublished research by Moxness and Lym (1989) showed that almost half of the ^{14}C -picloram that translocated to leafy spurge roots was released into the root media. Except for the surface wash of the harvested buds, picloram was not quantified in other organ tissues, nor in the root media in the present study.

Although ^{12}C -picloram sprayed onto the vermiculite surface of potted leafy spurge crowns was the least effective of the picloram treatments, it still resulted in significant inhibition of bud elongation. Thus picloram was able to move through the vermiculite and reach the crown buds at levels apparently high enough to cause inhibition. A possible reason why picloram is so effective in the control of leafy spurge may be its ability to directly target the crown buds. Sterling and Lownds (1992) found evidence to support simple diffusion across the cuticle as the mechanism of picloram absorption in broom snakeweed (*Gutierrezia sarothrae*) and this appears to support the finding in the ^{14}C -picloram experiment that picloram uptake was greater for the larger leafy spurge buds, although bud surface area was not directly measured.

Although the effects of glyphosate applied directly to crown buds were not statistically significant, the results do suggest that some glyphosate absorption had occurred. Glyphosate at the "low" rate did initially cause a reduction in bud elongation but after ten days a sharp increase in bud elongation occurred and reached values greater than the control treatment after 15 days. This apparent stimulatory effect of glyphosate is consistent with the findings of Maxwell *et al.* (1987) who found that glyphosate at sublethal rates facilitated prolific shoot bud growth from previously inhibited buds on leafy spurge plants. Glyphosate at sublethal rates has caused tillering as well as root and axillary bud growth in other species (Waldecker and Wyse 1985, Lee 1984, Baur *et al.* 1977, Coupland and Caseley 1975). Apparently glyphosate has the ability to alter the bud dormancy regulation system (Lee 1984, Maxwell *et al.* 1987). Since glyphosate does not persist in soil, glyphosate would never be available in the soil under field conditions to directly contact the crown buds.

Field Cover of Herbicide Treated and Burned Plots

A late season application of picloram (at 0.5 and 1.0 lb ai/acre) significantly reduced the cover of leafy spurge during the two years following treatment. Glyphosate (1.0 lb ai/acre) applied late in the season resulted in reduced spurge cover initially followed by a significant increase in cover before dropping back down to cover values similar to the control treatment. These results are in agreement with those of Maxwell *et al.* (1987) who found that a fall application of glyphosate resulted in a twofold increase in the number of leafy spurge stems.

Apparently, bud elongation is inhibited in the spring when the internal levels of glyphosate are high but as the glyphosate levels decline to sublethal levels during the summer, the glyphosate interferes with correlative inhibition causing a release of previously inhibited crown buds as well as axillary shoot buds (Maxwell *et al.* 1987). After one year following a fall glyphosate treatment, the rapid loss of leafy spurge control (Lym and Messersmith 1985) and the heavy re-infestation of leafy spurge (Gylling and Arnold 1983) were both attributed to leafy spurge seedling establishment but rather may have been caused by the stimulation of buds on the mature plants by low levels of glyphosate.

Some previous unpublished work by one of the authors of the present study (David D. Biesboer) indicated that a fall herbicide application followed by a burn was effective at controlling leafy spurge. In the present study, the fall burn had to be delayed until the following spring because of a snowstorm. Analysis of the data indicated that the burn treatment had no effect on the above-ground cover of leafy spurge. The delay in burning until spring, as well as the low fuel load at the site which resulted in a patchy fire of low intensity, may have been contributing factors to the lack of response of leafy spurge above-ground cover to the burn. Alternatively, burning prior to a herbicide application of picloram has been found to enhance leafy spurge control by removing plant litter thereby increasing the visibility of leafy spurge plants and allowing more herbicide to reach the root zone (McOwen 1990, Winter 1992). Fall burning not followed by a picloram application did not result in a significant setback of leafy spurge (McOwen 1990).

Conclusions

A late season application of picloram has proven to be more effective than glyphosate at controlling leafy spurge perhaps due to its ability to persist in soil and directly target the crown buds. Since crown bud elongation begins shortly after flowering in the spring, an application of picloram at any time thereafter would be injurious to leafy spurge crown buds. Leafy spurge control has been found to be greatest when picloram is applied in mid June or after late August (Lym and Messersmith 1991). The effectiveness of a late season (October) application of picloram can probably be attributed to the crown buds greater size at this time and therefore greater surface area for which picloram absorption from the soil can occur, and for the reduced time for new buds to regenerate before the onset of winter. A fall application of glyphosate at 1.0 lb ai/acre would not be recommended because of the prolific shoot growth which occurs when glyphosate levels decline. Burning was not effective at increasing the control of leafy spurge when conducted in the spring subsequent to a fall herbicide application.

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Chapter 4. Recommendations

It is recommended that an integration of weed control practices using interfering species be used to control leafy spurge and Canada thistle. To be successful, an integrated approach should be designed for the specific land use and location (Lym 1992). In order to maintain acceptable weed control, continual monitoring of the sites are necessary so that control measures can be re-initiated when needed (Beck 1992).

The following is a list of recommendations for leafy spurge and Canada thistle control based on the findings of the present study:

1. Establish Minnesota native prairie grasses in weed infested areas. Generally, use short prairie grasses such as little bluestem, side-oats grama, and buffalograss for dry sites and tall prairie grasses such as big bluestem, switchgrass, and indiagrass in the more mesic sites.
2. Do not attempt to establish native prairie grasses in areas containing reed canary grass unless erosion can be controlled and reed canary grass can be eliminated with successful annual treatments with glyphosate.
3. Pretreat the site in the spring with the herbicide glyphosate prior to seeding.
4. To ensure a good establishment of the native prairie grasses, apply various management tools such as mowing (to a height of about eight inches), burning in early spring, and herbicide applications during the first two years as needed. Periodic spring burning will be necessary to maintain a vigorous native prairie grass stand.
5. The herbicides picloram at 0.5 to 1.0 lb/acre or imazethapyr at 0.25 lb/acre should be applied in the fall (September-October) as needed to maintain leafy spurge at acceptable levels.
6. The herbicide glyphosate (1.0 lb ai/acre) should not be applied in the fall for leafy spurge control because of the prolific shoot growth which occurs when glyphosate levels decline.

The following is a list of control recommendations for leafy spurge in various habitats compiled by Beck (1992):

1. **Open rangeland or pastures** - herbicides picloram (spring or fall applied at 1.0 to 2.0 lbs/acre), picloram + 2,4-D (spring applied at 0.25 + 1.0 lb/acre, respectively), dicamba (spring applied at 2.0 lbs/acre), or dicamba + 2,4-D (biannual application at 1.0 + 2.0 lbs/acre, respectively).
2. **Near water** - herbicides fosamine (spring applied at 6 to 8 lbs/acre), 2,4-D amine (biannual applications), or glyphosate (fall applied at 0.75 lbs/acre). Biological control.
3. **Among trees** - herbicides glyphosate or 2,4-D amine. Biological control.
4. **Non-crop areas** - herbicides picloram, picloram + 2,4-D, dicamba, or dicamba + 2,4-D. Applications of sulfometuron (fall applied at 0.2 lbs/acre) can be used if grass injury can be tolerated.

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Appendix A. Seed information.

Table A. Information of species used in field experiments.

Species	Cultivar	Source	Origin
Big bluestem <i>Andropogon gerardii</i> Vitman	MN common	Prairie Restorations Inc. Princeton, MN	Sher. Co. MN
Indian grass <i>Sorghastrum nutans</i> (L) Nash	MN common	Prairie Restorations Inc. Princeton, MN	Anoka Co. MN
Switch grass <i>Panicum virgatum</i> L.	Forestburg ----- MN common	Prairie Restorations Inc. Princeton, MN	SW MN and SD ----- Isanti Co. MN
Little bluestem <i>Schizachyrium scoparium</i> (Michx.) Nash	MN common	Prairie Restorations Inc. Princeton, MN	Benton Co. MN
Side oats grama <i>Bouteloua curtipendula</i> (Michx.) Torr.	MN common ----- Pierre	Prairie Moon Nursery, Winona, MN. ----- Prairie Restorations Inc. Princeton, MN	 ----- SD
Buffalograss <i>Buchloe dactyloides</i> (Nutt.) Engelm.	Sharp's improved, treated	Sharp Bros. Seed Co. Clinton, MO	Kansas
Pubescent wheatgrass <i>Agropyron intermedium</i> var. <i>trichophorum</i> (Link) Halac	Luna	Sharp Bros. Seed Co. Clinton, MO	KS
Crested wheatgrass <i>Agropyron cristatum</i> (L.) Gaertn.	Ephriam	Sharp Bros. Seed Co. Clinton, MO	KS
Western wheatgrass <i>Agropyron smithii</i> Rydb.	Arriba		UCEPC
Russian wildrye <i>Psathyrostachys juncea</i> (Fisch.) Nevski	Bozoisky		Bridger Montana
Mountain brome <i>Bromus sitchensis</i> Trin.	Hakari		
Smooth brome <i>Bromus inermis</i> Leyss.	Tiki		
Brome grass <i>Bromus</i> sp.	Matua	Challenge Seeds	
Alfalfa <i>Medicago sativa</i> L.	Spredor 2	Northrup King, Stanton, MN	
Alfalfa <i>Medicago sativa</i> L.	Ramsey	The MN Crop Improvement Assn. St. Paul, MN	MN

