



Integrating herbicides, fertilizer, and grazing to manage spotted knapweed infested rangeland
by JoElla Ray Carter

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Agronomy

Montana State University

© Copyright by JoElla Ray Carter (1999)

Abstract:

Spotted knapweed (*Centaurea maculosa* Lam.) is rapidly invading rangeland throughout the northwestern United States, decreasing forage production, plant species diversity, and wildlife habitat. Spotted knapweed management may be enhanced by integrating strategies beyond that of control that stimulate and maintain competitive grasses. The objective of the first study was to determine if picloram, fertilizer, and timing and frequency of grass defoliation affect spotted knapweed reinvasion. Sixteen chemical treatments (4 picloram rates [0.00, 0.14, 0.28, and 0.42 kg a.i. ha⁻¹] and 4 fertilizer rates [0, 66, 132, and 198 kg ha⁻¹ (16-20-0:N-P-K)]) were applied in the spring of 1994 to 4 m by 4 m plots and factorially arranged in a randomized-complete-block design. Within each plot, 6 defoliation treatments were randomly applied to 1 m by 1 m sub-plots. The defoliation treatments were grass only clipped to 60% utilization during the summer, fall, spring, alternating spring/fall, all three seasons, and the control received no defoliation.

The experiment was replicated 4 times at 2 sites dominated by spotted knapweed. At peak standing crop in 1997, spotted knapweed density, grass and spotted knapweed biomass, and percent cover of spotted knapweed, grass, litter, and bare-ground were measured, and analyzed as a split plot design at each site. Four years after treatment, all picloram rates reduced spotted knapweed density and biomass. Fertilizer and defoliation in all three seasons caused a greater increase in spotted knapweed reinvasion at the site with Kentucky bluegrass (*Poa pratensis* L.) than the site with timothy (*Phleum pratense* L.) and smooth brome (*Bromus inermis* Leys.). Fall-only defoliation and no defoliation appear to deter spotted knapweed reinvasion better than defoliation in all three seasons and alternating spring/fall.

The objective of the second study was to determine the effects of integrating 2,4-D and repeated sheep grazing on spotted knapweed infested plant communities. Four treatments were replicated three times in a randomized-complete-block design at each site. The treatments were: 1) 2,4-D amine (2.1 kg ha⁻¹) applied in the spring, 2) sheep grazing (95% knapweed utilization) repeated three times in 1998, 3) 2,4-D amine (2.1 kg ha⁻¹) applied in the spring and sheep grazing (95% knapweed utilization) repeated three times in 1998, and 4) a control which did not receive 2,4-D or sheep grazing. Spotted knapweed density, grass and spotted knapweed biomass, and percent cover of spotted knapweed, downy brome (*Bromus tectorum* L.), other grasses, litter, and bare-ground were measured at peak standing crop in 1998. Data were analyzed using analysis of variance. Main effects of both sheep grazing and 2,4-D application lowered spotted knapweed seed head density and biomass. At Site 1, 2,4-D increased downy brome biomass and cover. However, when sheep grazing was combined with 2,4-D, downy brome biomass and cover were lowered from that of the 2,4-D alone. Sheep grazing alone had bare-ground and litter cover similar to that of the control, while plots treated with 2,4-D had higher bare-ground cover and lower litter cover.

**INTEGRATING HERBICIDES, FERTILIZER, AND GRAZING TO MANAGE
SPOTTED KNAPWEED INFESTED RANGELAND**

by

JoElla Ray Carter

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Agronomy

MONTANA STATE UNIVERSITY-BOZEMAN
Bozeman, Montana

January 1999

N378
C2457

APPROVAL

of a thesis submitted by

JoElla Ray Carter

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

Dr. Roger Sheley

Roger F. Sheley
(Signature)

Jan 7, 1999
(Date)

Approved for the Department of Land Resources and Environmental Sciences

Dr. Jeff S. Jacobsen

Jeff Jacobsen
(Signature)

1/7/99
(Date)

Approved for the College of Graduate Studies

Dr. Bruce R. McLeod

Bruce R. McLeod
(Signature)

1-8-99
(Date)

STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University-Bozeman, I agree that the library shall make it available to borrowers under rules of the library.

If I have indicated my intention to copyright this thesis by including a copyright notice page, copying is allowable only for scholarly purposes, consistent with "fair use" as prescribed in U.S. Copyright Law. Requests for permission for extended quotation from or reproduction of this thesis in whole or in parts may be granted only by the copyright holder.

Signature

Joella R. Carter

Date

1/7/99

TABLE OF CONTENTS

		Page
1.	LITERATURE REVIEW	1
	Introduction	1
	Existing Infestations	2
	Effects of Invasion	3
	Habitat	4
	Life History	5
	Control	7
	Cultural	7
	Burning	8
	Grazing	8
	Biological	8
	Chemical	10
	Integrated Pest Management	11
	Literature Cited	13
2.	EFFECT OF PICLORAM, FERTILIZER, AND DEFOLIATION ON SPOTTED KNAPWEED REINVASION	19
	Introduction	19
	Materials and Methods	22
	Study Sites	22
	Experimental Design	23
	Sampling	24
	Data Analysis	24
	Results	24
	Density	24
	Biomass	26
	Cover	28
	Discussion	30
	Literature Cited	33

TABLE OF CONTENTS - Continued

	Page
3. INTEGRATING 2,4-D AND SHEEP GRAZING TO MANAGE SPOTTED KNAPWEED INFESTED RANGELAND	36
Introduction	36
Materials and Methods	38
Study Sites	38
Experimental Design	39
Sampling	40
Data Analysis	40
Results	40
Density	40
Biomass	41
Cover	42
Discussion	42
Literature Cited	45
APPENDIX A (TABLES 1-6)	48
APPENDIX B (FIGURES 1-13)	55

LIST OF TABLES

Table	Page
1. Model components, degrees of freedom (Df), and mean squares for spotted knapweed density (plants m ⁻²).	49
2. Model components, degrees of freedom (Df), and mean squares for spotted knapweed and grass cover (%) and biomass (kg ha ⁻¹).	50
3. Model components, degrees of freedom (Df), and mean squares for cover (%) of litter and bare-ground.	51
4. Model components, degrees of freedom (Df), and mean squares for spotted knapweed density (plants m ⁻² and seed heads m ⁻²).	52
5. Model components, degrees of freedom (Df), and mean squares for spotted knapweed, downy brome, and other grass biomass (kg ha ⁻¹).	53
6. Model components, degrees of freedom (Df), and mean squares for spotted knapweed (Sk), grass (Gr), litter (Lt), bare-ground (Bg), and downy brome (Db) cover (%).	54

LIST OF FIGURES

Figure		Page
1.	Effect of fertilizer by picloram on total spotted knapweed density.	56
2.	Effect of defoliation by fertilizer on total spotted knapweed density.	57
3.	Effect of defoliation by picloram on juvenile spotted knapweed density.	58
4.	Effect of fertilizer by picloram on juvenile spotted knapweed density.	59
5.	Effect of fertilizer by picloram on spotted knapweed biomass.	60
6.	Effect of defoliation by fertilizer on spotted knapweed biomass.	61
7.	Effect of defoliation by picloram on grass biomass.	62
8.	Effect of fertilizer by picloram on grass cover.	63
9.	Effect of defoliation by picloram on litter cover.	64
10.	Effect of sheep grazing by 2,4-D on juvenile spotted knapweed density.	65
11.	Effect of sheep grazing by 2,4-D on spotted knapweed biomass.	66
12.	Effect of sheep grazing by 2,4-D on downy brome biomass.	67
13.	Effect of sheep grazing by 2,4-D on grass cover.	68

ABSTRACT

Spotted knapweed (*Centaurea maculosa* Lam.) is rapidly invading rangeland throughout the northwestern United States, decreasing forage production, plant species diversity, and wildlife habitat. Spotted knapweed management may be enhanced by integrating strategies beyond that of control that stimulate and maintain competitive grasses. The objective of the first study was to determine if picloram, fertilizer, and timing and frequency of grass defoliation affect spotted knapweed reinvasion. Sixteen chemical treatments (4 picloram rates [0.00, 0.14, 0.28, and 0.42 kg a.i. ha⁻¹] and 4 fertilizer rates [0, 66, 132, and 198 kg ha⁻¹ (16-20-0:N-P-K)]) were applied in the spring of 1994 to 4 m by 4 m plots and factorially arranged in a randomized-complete-block design. Within each plot, 6 defoliation treatments were randomly applied to 1 m by 1 m sub-plots. The defoliation treatments were grass only clipped to 60% utilization during the summer, fall, spring, alternating spring/fall, all three seasons, and the control received no defoliation. The experiment was replicated 4 times at 2 sites dominated by spotted knapweed. At peak standing crop in 1997, spotted knapweed density, grass and spotted knapweed biomass, and percent cover of spotted knapweed, grass, litter, and bare-ground were measured, and analyzed as a split plot design at each site. Four years after treatment, all picloram rates reduced spotted knapweed density and biomass. Fertilizer and defoliation in all three seasons caused a greater increase in spotted knapweed reinvasion at the site with Kentucky bluegrass (*Poa pratensis* L.) than the site with timothy (*Phleum pratense* L.) and smooth brome (*Bromus inermis* Leys.). Fall-only defoliation and no defoliation appear to deter spotted knapweed reinvasion better than defoliation in all three seasons and alternating spring/fall.

The objective of the second study was to determine the effects of integrating 2,4-D and repeated sheep grazing on spotted knapweed infested plant communities. Four treatments were replicated three times in a randomized-complete-block design at each site. The treatments were: 1) 2,4-D amine (2.1 kg ha⁻¹) applied in the spring, 2) sheep grazing (95% knapweed utilization) repeated three times in 1998, 3) 2,4-D amine (2.1 kg ha⁻¹) applied in the spring and sheep grazing (95% knapweed utilization) repeated three times in 1998, and 4) a control which did not receive 2,4-D or sheep grazing. Spotted knapweed density, grass and spotted knapweed biomass, and percent cover of spotted knapweed, downy brome (*Bromus tectorum* L.), other grasses, litter, and bare-ground were measured at peak standing crop in 1998. Data were analyzed using analysis of variance. Main effects of both sheep grazing and 2,4-D application lowered spotted knapweed seed head density and biomass. At Site 1, 2,4-D increased downy brome biomass and cover. However, when sheep grazing was combined with 2,4-D, downy brome biomass and cover were lowered from that of the 2,4-D alone. Sheep grazing alone had bare-ground and litter cover similar to that of the control, while plots treated with 2,4-D had higher bare-ground cover and lower litter cover.

CHAPTER 1

LITERATURE REVIEW

Introduction

Spotted knapweed (*Centaurea maculosa* Lam.), a native of Eurasia, is rapidly invading rangeland throughout the northwestern United States and Canada (Watson and Renney 1974, Strang et al. 1979, Harris and Cranston 1979). Spotted knapweed infests almost 2.2 million hectares of grassland in Montana and has been spreading at about 27% per year (Chicoine et al. 1985, Lacey et al. 1989). It also infests about 10,000 hectares in eastern Washington (Roché 1988) and British Columbia (Cranston 1988) and can be found throughout most of the northwestern United States.

The perennial growth habit, profuse seed production, and deep taproot of spotted knapweed enable rapid establishment and spread. Initial infestations occur in disturbed areas such as roadsides, trails, construction sites, overgrazed rangeland, and waterways (Watson and Renney 1974). Once established, spotted knapweed is very competitive, displacing native grasses and forbs, resulting in near monocultures of spotted knapweed (Davis 1990). Another factor contributing to the success of this weed in North America is the lack of natural enemies. In its center of origin, many host-specific insects and pathogens, grazing animals, and competitive plant species keep plant frequency and density at low levels (Turner 1986).

Spotted knapweed reduces forage production (Watson and Renney 1974, Harris and Cranston 1979), wildlife habitat (Bedunah and Carpenter 1989), and plant species diversity (Tyser and Key 1988). Knapweed infestations also increase bare-ground (Tyser

and Key 1988), surface water runoff and stream sedimentation (Lacey et al. 1989), and management costs.

Existing Infestations

Spotted knapweed was introduced into North America in 1893 from Eurasia in alfalfa seed (Groh 1940). Spotted knapweed can be found throughout most of the northwestern United States and southwestern Canada. It currently infests approximately 10,000 hectares in eastern Washington (Roché 1988) and British Columbia (Cranston 1988).

The first reported infestation in Montana was in Ravalli County during the middle 1920's (Bucher 1984). It can now be found in all 56 counties in Montana (French and Lacey 1983). Spotted knapweed currently infests about 2.5 million hectares of grassland in Montana (Chicoine et al. 1985, Lacey et al. 1989). Nearly 14 million hectares of Montana's range and grazable woodland is estimated to be vulnerable to invasion by spotted knapweed (Bucher 1984). Woodland with ponderosa pine (*Pinus ponderosa* Dougl. ex Laws. & Laws.) or Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) and foothills prairie vegetation dominated by bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) Scribn. & Smith), needle-and-thread grass (*Stipa comata* Trin. & Rupr.), or Idaho fescue (*Festuca idahoensis* Elmer) is nearly always vulnerable to invasion by spotted knapweed (Chicoine 1984).

Effects of Invasion

Spotted knapweed invasion is detrimental to soil and water resources. Lacey et al. (1989) found that surface runoff and interrill erosion are greater from spotted knapweed dominated sites than from similar bunchgrass dominated sites. Increased runoff and erosion can lead to loss of topsoil and sedimentation of reservoirs and water resources. Invasion by this weed can also alter plant community composition. Species richness and the frequency of several desirable species were inversely related to spotted knapweed density in Glacier National Park (Tyser and Key 1988).

Spotted knapweed is known to displace desirable forage species (Harris and Cranston 1979, Maddox 1979, Morris and Bedunah 1984, Watson and Renny 1974). It also reduces the availability of desirable forage species because of its dense, spiny canopy (Watson and Renny 1974). In forest clear-cuts, spotted knapweed was found to reduce tree seedling survival and wildlife forage (Willard et al. 1988). Many studies indicate that elk have a strong preference for grass during the winter and spring. Mooers (1986) reported that knapweed grew on every habitat type in western Montana, but was best adapted to drier grassland types, many of which are important sites for overwintering elk. Spotted knapweed is spreading throughout Glacier National Park's fescue grasslands which serve as important elk winter range. Spoon et al. (1983), referring to the noxious weed problems of the Lolo National Forest, stated, "The forage production lost on big game winter ranges could theoretically result in a loss of 220 elk, annually. The resulting loss of big game population has an adverse effect on hunter success, incomes of outfitters, and the state's tourist industry."

One of the most important impacts of noxious weeds to agriculture is the loss of livestock forage. Spotted knapweed threatens the long-term productivity of native rangelands. Grazing capacities of infested rangeland have been reduced by 63% (Bucher 1984). Spotted knapweed currently has the potential to reduce the gross revenue of Montana's livestock industry by \$155 million annually (Bucher 1984). If all vulnerable land became infested, loss estimates would be about \$1.7 billion, almost three times the current annual gross income from cattle and sheep (Bucher 1984). Land and weed managers of Montana spend over \$50 million per year combating noxious weeds on rangeland and along roadways (Montana Department of Agriculture 1994).

Habitat

Spotted knapweed is well adapted to a wide range of environmental conditions. It has been observed at altitudes ranging from 30 m to over 2700 m (Watson and Renny 1974, Chicione 1984) and in annual precipitation zones that receive less than 25.4 cm and more than 200 cm annually (Chicione 1984).

Spotted knapweed readily colonizes soil with a wide range of chemical and physical properties. The degree of soil disturbance, rather than specific soil properties, determines the potential density of the weed (Watson and Renny 1974). Although open habitats are preferred by spotted knapweed (Watson and Renny 1974), it will invade disturbed forest soils which have an intermittent canopy cover (Lacey, 1985).

Spotted knapweed is not a problem on cultivated lands. While environmental conditions may be able to support growth, frequent cultivation and chemical applications

eliminate these populations (Bucher 1984). It also is not likely to establish in saturated or poorly drained wetlands.

Life History

Spotted knapweed seeds are disseminated as a dry, indehiscent single seeded fruits called achenes, commonly referred to as cypseals in spotted knapweed because they are produced from an epigymous flower (Velagala 1996). These seeds germinate in the fall and spring, when soil moisture conditions are most favorable. Seedlings that germinate in the fall overwinter as rosettes and bolt the following summer. Seedlings established in the spring usually flower the following season (Schirman 1981).

Under optimum conditions, knapweed seeds imbibe water and germinate within 18 hours (Chicoine 1984). Spears et al. (1980) and Eddleman and Romo (1988) examined canopy cover, depth of emergence of seedlings, temperature, and moisture to determine the optimum conditions for germination. Canopy cover had no effect on germination of buried seed. Maximum germination occurred at soil moisture levels of 118 to 127% field capacity at soil temperatures ranging from 10° to 28° C. Seedlings did not emerge from depths of 3 cm and 5 cm for diffuse (*Centaurea diffusa* L.) and spotted knapweed, respectively. The highest percent germination occurred when seeds were left on the soil surface.

Nolan and Upadhyaya (1988) reported three types of germination behavior in freshly harvested spotted and diffuse knapweed seeds : 1) nondormant seeds that germinated in darkness, 2) light-sensitive dormant seeds that germinate in response to red

light, and 3) light-insensitive dormant seeds that fail to germinate in response to red light. Seeds of all three germination types were found on individual plants of both species.

Early germination and rapid growth rates enable spotted knapweed to capture resources before competitors (Sheley et al. 1993). Polymorphic germination behavior is a common phenomenon among weed species which insures seed germination for an extended period of time (Bewley and Black 1982). Knapweeds (*Centaurea* spp.) display germination and emergence polymorphism, which allows them to avoid intraspecific competition and occupy all available safe-sites by developing a hierarchy of age classes within the population (Sheley and Larson 1996).

Rosettes begin to bolt and immature flowers are first observed in mid-June. Two year old plants typically produce one to six stems per plant, and other plants typically produce more than a dozen branches (Watson and Renny 1974). Stems and branches elongate and flower heads continue to appear on the end of each branch throughout the summer. Flowering begins in mid-July. Individual flowers remain open for two to six days (Davis 1990). Knapweed species are cross-pollinated by insects and mature seeds are produced 18 to 26 days after fertilization (Watson and Renny 1974)

Spotted knapweed has high seed output and longevity, enabling regeneration after herbicidal control (Watson and Renny 1974, Schirman 1981, Davis et al. 1993, Kalisz and McPeck 1993). Under favorable conditions spotted knapweed can produce up to 349 seeds per plant, with 80% viability (Watson and Renny 1974) and up to 48,000 seeds per square meter (Schirman 1981). The bracts enclosing the flower heads begin to open approximately three weeks after maturity (Watson and Renny 1974). As relative humidity

fluctuates, the bracts open and close loosening the seeds and causing them to rise to the top of the capitulum (Watson and Renny 1974). Seeds are disseminated up to one meter by the flicking motion caused when the plants are moved abruptly (Strang et al. 1979).

Spotted knapweed is also spread by animals and man. The bristles of the pappus enable the seeds to loosely adhere to animal hair or human clothing, allowing transport (personal observation). Motorized vehicles are partially responsible for the long-distance spread of spotted knapweed in North America (Watson and Renny 1974, Mass 1985). This weed also spreads along waterways because of its waxy pericarp and bristly pappus tends to trap air (Davis 1990).

Seed bank viability plays an important role in the long-term survival of spotted knapweed populations. Seeds can remain dormant and viable in the soil for up to eight years (Davis and Fay 1991). Lacey (1985) projected that the soil seed bank can easily outlast the current herbicide treatments; therefore, retreatment is necessary to prevent replenishing the soil seed bank.

Control

Cultural

Spotted knapweed is easily controlled by repeated cultivation. Spears et al. (1980) found that spotted knapweed seeds did not emerge when the seeds were placed 5 cm below the soil surface. Spotted knapweed seeds can also be depleted through attrition if seed production is prevented or significantly reduced by mowing at the flowering stage (Watson and Renny 1974). Spotted knapweed infested land should be reseeded with a

vigorous grass or legume species after plowing to suppress reinfestation (Harris and Cranston 1979).

Burning

Dry structures of knapweeds persist for years and they burn readily (Carpenter 1986). Strang et al. (1979) reported that spotted knapweed rarely invades burned areas. According to Zednai (1968), spotted knapweed seed germination was reduced from 68% to 3% after a burn. However, Chicoine (1984) reported that burning did not reduce the seed bank of a natural spotted knapweed population.

Grazing

Nutrient content of spotted knapweed is adequate to meet livestock needs during early summer and spring when the stems are succulent and actively growing (Kelsey and Mihalovich 1987). However, Kelsey and Mihalovich (1987) also reported that cnicin (sesquiterpene lactone) in spotted knapweed imparts a bitter taste and may decrease palatability. Low to moderate levels of grazing of spotted knapweed by sheep, goats, and cattle have been reported in Montana (Cox 1989, Robertson 1989). Recently, Olson et al. (1997) found that areas repeatedly grazed by sheep had lower densities of seedlings, rosettes, and mature spotted knapweed plants than ungrazed areas. They also found that the number of spotted knapweed seeds in the soil was reduced after three years of intensive sheep grazing.

Biological

In Eurasia, a complex of monophagous insects feed on knapweed, limiting knapweed populations to small patches. A major factor contributing to the success of

knapweed in North America is the lack of natural enemies. The first biological control agent to be employed against knapweeds in the United States and Canada was the European seed head fly, *Urophora affinis* (Harris 1980). In 1973, the Tephritidae fly was released in Montana and Oregon (Story and Anderson 1978, Maddox 1982). Story (1989) reported that if screening tests proceed satisfactorily, a total of 11 insects will soon be introduced against spotted knapweed. Seed production by spotted knapweed has been reduced by 50 -75% by insects feeding on seed heads (Story et al. 1991). Harris (1980) reported up to 95% reduction in seed production in British Columbia. *Metzneria paucipunctella*, a seed head moth released in 1973 in British Columbia, has now spread to Montana, Idaho, Oregon, and Washington.

Harris (1980) reported that seed head flies were ineffective in reducing knapweed populations. Schirman (1981) estimated that only 0.1% survival of seeds produced was required to maintain infestations. Likewise, in a growth chamber study, Sheley and Jacobs (1996) found that 45% control of spotted knapweed did not alter the competitive balance from spotted knapweed to favor of bluebunch wheatgrass.

Root feeding insects reduce root storage capacity and uptake of water, and enhance susceptibility to pathogens. *Agapeta zoegana* L., *Pelochrista medullana* Stgr., *Pteroloche inspersa* Stgr., *Cyphocleonus achates* Fahr., all root feeding insects were selected for introduction between 1979 and 1983 (Muller et al. 1988). *A. zoegana* is the most promising insect introduced for control of spotted knapweed. Heavy attack by the larvae of this moth can cause death to small plants (Muller et al. 1988). Harris and

Cranston (1979) suggested that the establishment of at least six natural enemies would be necessary for effective biological control of spotted knapweed.

Plant pathogens have been investigated for their potential as biological control agents. Host specificity is one of the major problems limiting the use of plant pathogens like *Puccinia* spp. (Watson and Clement 1986). *Scelrotinia sclerotiorum* (Lib) de Bary, is a soil borne fungus with a wide host range (Purdy 1979). Jacobs et al. (1996) found *S. sclerotiorum* reduced spotted knapweed density by 68 to 80% without reducing bluebunch wheatgrass density. They also found that *S. sclerotiorum* reduced individual spotted knapweed plant weight. Long-term control of spotted knapweed using biological control agents may be effective combined with other weed control methods (Cuda et al. 1989).

Chemical

Long-term, sustained control of spotted knapweed is difficult to achieve.

Two,4-D, (2,4-dichlorophenoxy acetic acid) applied from bolt to early flowering stage provides adequate control of spotted knapweed (Lacey et al. 1986). Reapplication of 2,4-D is necessary to control regrowth of older established plants (Lacey 1985). Ester formulations of 2,4-D are more effective than amines (Belles et al. 1978). Dicamba (3,6-dichloro-o-anisic acid) gives about two years control of spotted knapweed (Fay et al. 1989).

Currently, some rangeland managers rely on repeated applications of persistent herbicides like picloram (4-amino-3,5,6 trichloro-2-pyridinecarboxylic acid) to control spotted knapweed. It is the most effective herbicide for long-term control of spotted knapweed (Lacey 1985). Efficacy of picloram depends on soil conditions, especially the

presence of organic matter, moisture, and temperature (Goring and Haymaker 1971). The time between application of picloram and occurrence of precipitation greatly influences the loss of picloram (Hall et al. 1968). Davis (1990) found that picloram applied at 0.07, 0.11, 0.14, 0.22, 0.25, and 0.28 kg a.i. ha⁻¹ provided four and seven years of control with 200 and 700% increase in grass yield, respectively at two sites in Montana. However, after picloram dissipates, spotted knapweed invades from its seed bank (Davis et al. 1993). Sheley and Jacobs (1997) found that picloram increased grass yield by an average of 1500 kg ha⁻¹, and reduced spotted knapweed density to zero two years after application. Clopyralid (3,6-dichloro-2-pyridinecarboxylic acid) is more selective than picloram and has a shorter soil residual period. It provided 100% control of spotted knapweed one year following application without affecting native forbs (Lacey et al. 1989).

Long term chemical control is cost-effective only on highly productive rangeland with a residual grass understory (Griffith and Lacey 1991). However, reseeding of spotted knapweed infested areas following herbicide treatment increases forage production by suppressing knapweed seedling establishment (Hubbard 1975).

Integrated Pest Management

Many managers of today's rangelands rely on repeated applications of persistent herbicides to control weeds. Although herbicides are an effective tool for controlling noxious weeds, repeated applications on large-scale infestations are rarely economically feasible. Other weed management tools, such as grazing and biological controls, offer promise for some weeds. In many cases, they need to be combined with other control methods to be effective (Sheley et al. 1996). It is becoming increasingly clear that

integrated weed management strategies need to be developed to provide viable, long-term solutions to noxious weed problems (Alley et al. 1984, Dershiel et al. 1985, Cuda et al. 1989, Sedivec and Muine 1993). Integrating control methods may have a synergistic effect on providing long-term, sustainable spotted knapweed control and enhancing forage production on rangelands (Sheley and Roche' 1982, Sheley et al. 1984, Turner 1986, Cuda et al. 1989). Little research has been conducted on integrated weed management practices for spotted knapweed infested rangeland. Developing integrated spotted knapweed management may provide the land managers of North America more sustainable and cost-effective methods for addressing weed infested rangeland.

Literature Cited

- Alley, H.P., N.E. Humberg, J. K. Fronsrou, and M. Ferrel. 1984.** Leafy spurge (*Euphorbia esula*) control with repetitive herbicide treatments. Res. Weed Science, Wyoming Agriculture Experiment Station Res J. 192:90-93.
- Bedunah, D. and J. Carpenter. 1989.** Plant community response following spotted knapweed (*Centaurea maculosa* L.) control on three elk winter ranges in western Montana. In: P.K. Fay and J.R. Lacey (eds.), Knapweed Symposium Proceedings, Montana State Univ., Bozeman, MT.
- Belles, W.S., D.W. Wattengarger, and G.A. Lee. 1978.** Spotted knapweed control. Proc. West. Soc. Weed Sci. 31:17-18.
- Bewley, J.D. and M. Black. 1982.** Physiology and biochemistry of seeds in relation to germination. Volume 1. Springer-Verlag, Berlin, Heidelberg, New York. 306 pp.
- Bucher, R.F. 1984.** Potential spread and cost of spotted knapweed on rangelands. MontGuide 8423, Montana State Univ., Bozeman, MT.
- Carpenter, J.L. 1986.** Response of three plant communities to herbicide spraying and burning of spotted knapweed in western Montana. M.S. Thesis, Univ. of Montana., Missoula, MT.
- Chicoine, T.K. 1984.** Spotted knapweed control, seed longevity, and migration in Montana. M.S. Thesis, Montana State Univ., Bozeman, MT.
- Chicoine, E.S., P.K. Fay, and G.A. Neilsen. 1985.** Predicting weed migration from soil and climate maps. Weed Sci., 34:57-61.
- Cox J.E. 1989.** Observations, experiments, and suggestions for research on sheep-spotted knapweed relationship. In: P.K. Fay and J.R. Lacey (eds.), Knapweed Symposium Proceedings, Montana State Univ., Bozeman, MT.
- Cranston, R. 1988.** British Columbia Survey. Knapweed (newsletter) Vol. 2.2.
- Cuda, J.P., B.W. Sindelar, and J.H. Cardellina. 1989.** Proposal for integrated management system for spotted knapweed (*Centaurea maculosa* L.). In: P.K. Fay and J.R. Lacey (eds.), Knapweed Symposium Proceedings, Montana State Univ., Bozeman, MT.

- Davis E.S. 1990.** Spotted knapweed (*Centaurea maculosa* L.) seed longevity, chemical control, and seed morphology. M.S. Thesis, Montana State Univ., Bozeman, MT.
- Davis E.S. and P.K. Fay. 1991.** Spotted knapweed seed remains viable in soil after eight years. Knapweed (newsletter) Vol. 5.2.
- Davis E.S., P. K. Fay, T.K. Chicoine, and C.A. Lacey. 1993.** Persistence of spotted knapweed. Weed Sci. 41:57-61.
- Dershiel, L.A., L.J. Wrage, and W.E. Arnold. 1985.** Cultural control of leafy spurge. p.57-64. In: A.K. Watsom (ed) Leafy Spurge Mangr. 3. Weed Science Soc. Am., Champagne, IL.
- Eddleman, L.E. and J.T. Romo. 1988.** Spotted knapweed germination response to stratification, temperature, and water stress. Can. J. Bot. 66:653-657.
- Fay, P.K., E.S. Davis, T.B. Chicoine, and C.A. Lacey. 1989.** The status of long-term chemical control of spotted knapweed. In: P.K. Fay and J.R. Lacey (eds.), Knapweed Symposium Proceedings, Montana State Univ., Bozeman, MT.
- French, R.A. and J.R. Lacey. 1983.** Knapweed, its cause, effect, and spread in Montana. Mont. Coop. Extension Service Bulletin 307. Montana State Univ., Bozeman, MT.
- Goring, C.A. and J.W. Haymaker. 1971.** The degradation and movement of picloram in soil and water. Down to Earth. 27:12-15.
- Griffith D. and J.R. Lacey. 1991.** Economic evaluation of spotted knapweed (*Centaurea maculosa* L.) control using picloram. J. Range Manage. 44:43-47.
- Groh, H. 1940.** Turkestan alfalfa as a medium of weed introduction. Sci. Agr. 21:36-43.
- Hall, R.C., C.S. Gram, and M.G. Merkle. 1968.** The photolytic degradation of picloram. Weed Res. 8:292-297.
- Harris, P. 1980.** Effects of *Urophora affinis* Frfld. and *U. quadrifasciata* (Meig.). (Diptera:Tephritidae) on *Centaurea diffusa* Lam. and *C. maculosa* Lam. (Compositae). Z. ang. Ent. 90:190-201.
- Harris, P. and R. Cranston. 1979.** An economic evaluation on control methods for diffuse and spotted knapweed in western Canada. Can. J. Plant Sci. 59:375-382.
- Hubbard, W.A. 1975.** Increased range forage production by reseeding and chemical control of knapweed. J. Range Manage. 28:406-407.

- Jacobs, J.S., R.L. Sheley, and B.D. Maxwell. 1996.** The effect of *Sclerotinia sclerotium* on the interference between bluebunch wheatgrass and spotted knapweed. *Weed Technol.* 10:13-21.
- Kalisz, S. and M.A. McPeck. 1993.** Extinction dynamics, population growth, and seedbanks. *Oecologia* 95:314-320.
- Kelsey, R.G. and R.D. Mihalovich. 1987.** Nutrient composition of spotted knapweed (*Centaurea maculosa*). *J. Range Manage.* 40:277-281.
- Lacey, C.A. 1985.** A weed education program, and biology and control of spotted knapweed (*Centaurea maculosa*) in Montana. M.S. Thesis, Montana State Univ. Bozeman, MT.
- Lacey, C.A., J.R. Lacey, T.K. Chicoine, P.K. Fay and R.A. French. 1986.** Controlling knapweed on Montana rangeland. *Circ. Montana State Univ. Coop. Ext. Service, Bozeman, MT.* 15 pp.
- Lacey J.R., C.B. Marlow, J.R. Lane. 1989.** Influence of spotted knapweed (*Centaurea maculosa*) on surface runoff and sedimentation yield. *Weed Technol.* 3:627-631.
- Maddox, D.M. 1979.** The knapweeds: Their economic and biological control in the western states, U.S.A. *Rangelands* 1:139-140.
- Maddox, D.M. 1982.** Biological control of diffuse knapweed (*Centaurea diffusa*) and spotted knapweed (*Centaurea maculosa*). *Weed Sci.* 30:76-82.
- Mass, F.H. 1985.** The knapweed-spurge invasion in Montana and the inland Northwest. *Western Wildlands* 10:14-19.
- Mooers, G.B. 1986.** The distribution of *Centaurea maculosa* in western Montana's habitat types. M.S. Thesis, Univ. of Montana. Missoula, MT.
- Morris, M.S. and D. Bedunah. 1984.** Some observations on the abundance of spotted knapweed (*Centaurea maculosa*) in western Montana. In: P.K. Fay and J.R. Lacey (eds.), *Knapweed Symposium Proceedings*, Montana State Univ., Bozeman, MT.
- Muller, H., D. Schroeder, and A. Gassmann. 1988.** *Agapeta zoegana* (L.) (Lepidoptera: Clchylidae), a suitable prospect for biological control of spotted and diffuse knapweed, *Centaurea maculosa* monnet de la marck and *Centaurea diffusa* monnet de la marck (Compositae) in north America. *Can. Entom.* 120: 109-124.

- Nolan, D.M. and T.K. Upadhyaya. 1988.** Primary seed dormancy in diffuse and spotted knapweeds. *Can. J. Plant Sci.* 63:981-987.
- Olson, B.E., R.G. Wallander, and J.R. Lacey. 1997.** Effects of sheep grazing on spotted knapweed infested Idaho fescue community. *J. Range Manage.* 50:386-390.
- Purdy, L.H. 1979.** *Sclerotinium sclerotiorum*: history, diseases, symptomology, host range, geographic distribution, and impact. *Phytopathology.* 69:875-880.
- Roché, C. 1988.** Washington Knapweed Survey. Knapweed (newsletter) Vol. 2.3.
- Robertson, K. 1989.** Living with spotted knapweed in the Bitterroot Valley. In: P.K. Fay and J.R. Lacey (eds.), Knapweed Symposium Proceedings, Montana State Univ., Bozeman, MT.
- Schirman, R. 1981.** Seed production and spring seedling establishment of diffuse and spotted knapweed. *J. Range Manage.* 34:45-47.
- Sedivec, K.K. and R.P. Muine. 1993.** Angora goat grazing as a biological control of leafy spurge: a 3 year summary. Proc. Leafy Spurge Symposium, GPC-14 Colorado State Univ. Ft. Collins, CO.
- Sheley, R.L. and B.F. Roché. 1982.** Rehabilitation of spotted knapweed infested rangeland in northwest Washington. Abstract. W. Soc. Weed Sci. Denver, CO.
- Sheley, R.L., R.H. Callihan, and C.H. Huston. 1984.** Improvement of spotted knapweed infested pastures with picloram and fertilizer. Montana State Univ. Coop. Ext. Service Bulletin 1315. pp 21-22.
- Sheley R.L., L.L. Larson, and D.E. Johnson. 1993.** Germination and root dynamics of range weeds and forage species. *Weed Technol.* 7:234-237.
- Sheley, R.L. and J.S. Jacobs. 1996.** "Acceptable" levels of spotted knapweed (*Centaurea maculosa*) control. *Weed Technol.* 11:363-368.
- Sheley, R.L. and L.L. Larson. 1996.** Emergence date effects on resource partitioning between diffuse knapweed seedlings. *J. Range Manage.* 49:241-244.
- Sheley, R.L., T.J. Svejcar, and B.D. Maxwell. 1996.** A theoretical framework for developing successional weed management strategies on rangeland. *Weed Technol.* 10: 766-773.

- Sheley, R.L. and J.S. Jacobs. 1997.** Response of spotted knapweed and grass to picloram and fertilizer combinations. *J. Range Manage.* 50:263-267.
- Spears, B.M., S.T. Rose, and W.S. Belles. 1980.** Effect of canopy cover, seeding depth, and soil moisture on emergence of *Centaurea maculosa* and *C. diffusa*. *Weed Res.* 20:87-90.
- Spoon, C.W., H.R. Bowles, and A. Kulla. 1983.** Noxious weeds on the Lolo National Forest. USDA Forest Service, Northern Region, situation analysis staff paper. Missoula, MT.
- Story, J.M. and N.L. Anderson. 1978.** Release and establishment of *Urophora affinis* (Diptera:Tephritidae) on spotted knapweed in western Montana. *Environ. Ent.* 7:445-448.
- Story, J.M. 1989.** The status of biological control of spotted and diffuse knapweed. In: P.K. Fay and J.R. Lacey (eds.), *Knapweed Symposium Proceedings*, Montana State Univ., Bozeman, MT.
- Story, J.M., K.W. Boggs, W.R. Good, P. Harris, and R.M. Nowierski. 1991.** *Metzneria paucipuntella* Zeller (Lepidoptera:Gelechiidae), a moth introduced against spotted knapweed: its feeding strategy and impact on two introduced *Urophora spp.* (Diptera:Tephritidae). *Can. Entomol.* 123:1003-1007.
- Strang, R.M., K.M. Lindsay, R.S. Price. 1979.** Knapweeds: British Columbia's undesirable aliens. *Rangelands* 1:141-143.
- Turner, C.E. 1986.** Conflicting interests and biological control of weeds. pp. 203-225. In: DelFosse, E.S. (Ed.). *Proc. 6th Int. Symp. Biol. Control of Weeds*. Vancouver, B.C. Canada.
- Tyser, R.W. and C.H. Key. 1988.** Spotted knapweed in a natural area fescue grassland: An ecological assessment. *Northwest Sci.* 62(4):151-160.
- Velagala, R.P. 1996.** Using seed rate and plant densities to enhance intermediate wheatgrass establishment in spotted knapweed dominated rangeland. M.S. Thesis, Montana State Univ., Bozeman, MT.
- Watson, A.K. and M. Clement. 1986.** Evaluation of rust fungi as biological control agents of weedy *Centaurea* in north America. *Weed Sci.* 34:7-10.
- Watson, A.K. and A.J. Renney. 1974.** The biology of Canadian weed. 6. *Centaurea maculosa* and *C. diffusa*. *Can. J. Plant Sci.* 54:687-701.

Willard E.E., D.J. Bedunah, and C.L. Marcum. 1988. Impacts and potential impacts of spotted knapweed (*Centaurea maculosa*) on forest and rangelands in western Montana. Montana Forest and Conserv. Exp. Stat., Final Rep., Missoula, MT. 264 pp.

Zednai, J.G. 1968. Studies on the biology and control of *Centaurea maculosa* L.. B. Sc. Thesis, Univ. of British Columbia.

CHAPTER 2

EFFECT OF PICLORAM, FERTILIZER, AND DEFOLIATION ON SPOTTED KNAPWEED REINVASION

Introduction

Spotted knapweed (*Centaurea maculosa* Lam.), a native of Eurasia, is rapidly invading rangeland throughout the northwestern United States and Canada (Watson and Renney 1974, Strang et al. 1979, Harris and Cranston 1979). Spotted knapweed has been spreading at about 27% per year and infests almost 2.2 million hectares of rangeland in Montana (Chicoine et al. 1985, Lacey et al. 1989). It also infests about 10,000 hectares in eastern Washington (Roché 1988) and British Columbia (Cranston 1988) and can be found throughout the northwestern United States.

Spotted knapweed reduces forage production (Watson and Renney 1974, Harris and Cranston 1979), plant species diversity (Tyser and Key 1988), and wildlife habitat (Bedunah and Carpenter 1989). Knapweed (*Centaurea* spp.) infestations also increase bare-ground (Tyser and Key 1988), surface water runoff (Lacey et al. 1989), stream sedimentation, and management costs.

The perennial growth habit, profuse seed production, and deep taproot of spotted knapweed result in rapid establishment and spread (Sheley et al. 1998). Initial infestations often occur in disturbed areas such as roadsides, trails, construction sites, overgrazed range, and waterways (Watson and Renney 1974). Once established, it is very competitive, displacing native grasses and forbs, and may result in nearly monocultural stands of spotted knapweed (Davis 1990). Another factor contributing to its success in

North America is the lack of natural enemies. In its center of origin, many host-specific insects and pathogens, grazing animals, and competitive plant species keep spotted knapweed frequency and density at low levels (Turner 1986).

Most broadleaf herbicides are effective in killing spotted knapweed, but new seedlings usually emerge within a year (Fay et al. 1989). Picloram (4-amino-3,5,6-trichloropicolinic acid) applied at a rate of 0.28 kg a.i. ha⁻¹ provides control for 2 to 5 years (Davis 1990). Although the persistence of picloram in the soil affects weeds for 12 to 30 months (Hamaker et al. 1967, Lacey 1985), extended control is enhanced by competition from residual perennial grasses that are released by herbicide application (Hubbard 1975, Chicoine 1984, Sheley et al. 1984, Roché 1988). Herbicide and fertilizer applications have increased forage production on rangelands (Dwyer and Schickendanz 1971, Hart et al. 1995); however, little is known about combining them to control knapweed and enhance forage production.

Integrating picloram and fertilizer may have a synergistic effect on providing spotted knapweed control and enhancing grass production. In a pilot study, Sheley and Roché (1982) combined picloram (0.28 kg a.i. ha⁻¹) and fertilizer (N+P: 17.9 + 22.4 kg ha⁻¹) which increased grass yield from about 275 (control) and 660 (picloram alone) to over 2,200 (picloram plus fertilizer) kg ha⁻¹, two years after application. In that study, knapweed control was also greater where picloram was combined with fertilizer. More recently, Sheley and Jacobs (1996) found picloram and fertilizer did not interact to affect spotted knapweed density or grass yield two years after application. All picloram treatments (0.14 to 0.42 kg a.i. ha⁻¹) reduced spotted knapweed to nearly zero.

Fertilization did not affect spotted knapweed density, but the highest rate (N+P: 31.7 + 39.6 kg ha⁻¹) increased grass yield on the site with a substantial grass understory.

At the rate of 0.28 kg a.i. ha⁻¹, picloram may provide 2 to 5 years of complete control (no seed production) due to soil residual activity (Fay et al. 1989). However, the spotted knapweed seed bank can easily outlast the residual herbicide (Davis 1990); therefore, all treated areas face the threat of reinvasion by spotted knapweed. One way to minimize reinvasion is to maximize the competitive ability of the residual grass understory. Competitive interactions between weeds and perennial grasses is affected by frequency, timing, and intensity of defoliation, which in turn affects the ability of a perennial grass community to withstand weed invasion (Maschinski and Whitham 1989, Briske 1990, Jacobs and Sheley 1997). Although studies suggest that moderate grass use does not accelerate the invasion of uninfested rangeland by spotted knapweed (Sheley et al. 1997, Jacobs and Sheley 1997), no studies attempt to quantify the effects of defoliation on the reinvasion of spotted knapweed after control.

The overall objective of this study was to determine the effect of timing and frequency of grass defoliation on spotted knapweed reinvasion in plots treated with picloram and fertilizer. Specific objectives were to: 1) determine if picloram and fertilizer interact to increase spotted knapweed control or grass yield, and 2) determine if timing and frequency of grass defoliation affected spotted knapweed reinvasion. My first hypothesis was that picloram and fertilizer would interact to increase spotted knapweed control and grass yield, which would limit reinvasion. The second hypothesis was that more frequent grass defoliations and defoliation in the spring would enable increased

spotted knapweed establishment compared to summer and fall defoliations and alternate spring/fall defoliation.

Materials and Methods

Study Sites

Field studies were conducted from 1994 through 1997 on two sites in western Montana to evaluate the effect of combining picloram, fertilizer, and grass defoliation to control spotted knapweed, enhance grass yield, and limit the reinvasion of spotted knapweed. The study sites were located near Bozeman, Montana (111°5'36" W, 45°35'26" N). Both sites were within a bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh) Scribn. & Smith) - Idaho fescue (*Festuca idahoensis* Elmer) habitat type (Daubenmire 1970) and were dominated by spotted knapweed.

Site 1 was an abandoned hayfield. Spotted knapweed density was 470 plants m⁻² (SD=140). The residual grass understory was co-dominated by two introduced species, smooth brome (*Bromus inermis* Leys) and timothy (*Phleum pratense* L.). The understory on Site 2 was dominated by Kentucky bluegrass (*Poa pratensis* L.). Spotted knapweed density was 140 plants m⁻² (SD=107). The soil at both sites was a complex consisting of 70% Beaverton cobbly loam (loamy-skeletal over sandy or sandy-skeletal mixed, Typic Argiborolls) and 30% Hyalite loam (fine-loamy, mixed, Typic Argiborolls) and had zero slope and an elevation of 1,340 m. Annual precipitation ranges from 381 to 483 mm, and the frost-free period ranges from 90 to 110 days at both sites.

Experimental Design

Sixteen chemical treatments (4 picloram rates, 4 fertilizer rates) were applied to 4 m by 4 m plots and factorially arranged in a randomized-complete-block design. Within each plot, six different defoliation treatments were randomly applied to 1 m by 1 m sub-plots. The experiment was replicated 4 times at each site. Picloram rates of 0.0, 0.14, 0.28, and 0.42 kg a.i. ha⁻¹ were applied in the spring of 1994 using a six-nozzle backpack sprayer delivering 130 liters ha⁻¹ spray solution. Granular fertilizer was broadcast at N+P rates of 0.0+0.0, 10.5+13.2, 21.1+26.4, and 31.7+39.6 kg ha⁻¹ (material: 0.0, 66, 132, 198 kg ha⁻¹) using a hand-held applicator. Both sites were treated on May 2, 1994, when the spotted knapweed was in the rosette stage. Air temperature, soil temperature (surface), and relative humidity were 17.5°C, 21°C, and 90%, respectively, at the time of application. Winds ranged from 0 to 6 km hr⁻¹. Individual plots were spatially separated by a 2.1 m buffer zone treated with 0.28 kg a.i. ha⁻¹ picloram to prevent spotted knapweed seed contamination from neighboring plots.

Beginning fall 1994 through fall 1997, all clippings removed approximately 60% of the above ground biomass of all grass species present in the sub-plots. The six clipping regimes differed in the frequency and timing of defoliation. They included an unclipped control, a mid-summer clipping each year, a spring clipping each year, a fall clipping each year, alternating spring/fall clipping each year, and clipping in all three seasons (spring, summer, and fall) each year.

Sampling

At peak standing crop (August), above-ground biomass within a 0.5 m² frame was harvested from each plot in 1997. Grass and spotted knapweed were separated and dried at 60°C and then weighed. Juvenile and total spotted knapweed densities (plants m⁻²) were counted in 0.1 m (2dm x 5dm) Daubenmire (1970) frames in each sub-plot at the time of harvest. Percent cover was visually estimated for spotted knapweed, all grass species, litter, and bare-ground at the time of harvest.

Data Analysis

Each site was analyzed separately. Data were analyzed in a split-plot design with chemical treatments (picloram + fertilizer) as whole plots and defoliation as sub-plots. Picloram, fertilizer, and their interaction were tested using rep*picloram*fertilizer as the error term. Defoliation, picloram*defoliation, fertilizer*defoliation, and the 3-way interaction were included in the model and tested using the residual error. When F-tests were significant (P < 0.05) differences among means were tested using least significant differences procedures.

Results

Density

Juvenile and total spotted knapweed densities were reduced by picloram four years after treatment at Site 1 (Table 1). All picloram rates lowered juvenile and total spotted knapweed densities below the control. Juvenile density was reduced from 143.8 plants m⁻² (0.0 kg a.i. ha⁻¹ picloram) to 33.3, 6.0, 1.1 plants m⁻² when picloram was applied at 0.14,

0.28, 0.42 kg a.i. ha⁻¹, respectively (LSD=45.9). Picloram applications of 0.14, 0.28, and 0.42 kg a.i. ha⁻¹ reduced total spotted knapweed densities to 49.3, 10.2, and 1.9 plants m⁻² from 192.1 plants m⁻² in the control (LSD=53.9).

Total spotted knapweed density was dependent on the interaction of herbicide and fertilizer at Site 2 (Table 1). Without herbicide, fertilizer applied at 132 kg ha⁻¹ provided total spotted knapweed densities higher than the other fertilizer rates (Figure 1). At all other herbicide rates spotted knapweed densities were similar.

At Site 2, the effect of defoliation on total spotted knapweed density was dependent upon the rate of fertilizer applied (Table 1). Total spotted knapweed density was similar among all defoliation treatments where no fertilizer was applied (Figure 2). At 66 kg ha⁻¹, defoliation in all three seasons had higher spotted knapweed density than plots defoliated in the spring, summer, or fall. Alternating spring and fall grass defoliation yielded higher spotted knapweed densities than spring defoliation only. All other treatments had similar knapweed density at that fertilizer level. However, at 132 kg ha⁻¹, defoliating grass in all three seasons had high total spotted knapweed density, but was similar to those plots defoliated each spring. Total spotted knapweed density was lowest in plots without defoliation, but was similar to plots defoliated alternately in the fall and spring at this fertilizer level. At 198 kg ha⁻¹, all defoliation treatments yielded similar total spotted knapweed density. Furthermore, total spotted knapweed density at this fertilizer level was similar to those where no fertilizer was applied.

At Site 2, the effect of grass defoliation on the density of juvenile spotted knapweed plants was dependent on the rate of picloram applied at site 2 (Table 1). Where

no picloram was applied, spring defoliation resulted in low juvenile spotted knapweed density, but it was similar to alternate spring/fall defoliation (Figure 3). Defoliation in the summer, fall, and all three seasons resulted in the highest densities of juvenile spotted knapweed plants. Picloram applied at 0.28 kg ha^{-1} yielded the higher juvenile spotted knapweed densities where the plots were defoliated alternately in the spring and fall than where they were not defoliated. Picloram applied at 0.14 and 0.42 kg ha^{-1} provided no significant differences among defoliation treatments.

Four years after treatment, the rate of picloram interacted with the amount of fertilizer applied to affect juvenile spotted knapweed density at Site 2 (Table 1). Where no picloram was applied, fertilizer applied at 66 kg ha^{-1} and 132 kg ha^{-1} provided higher juvenile spotted knapweed density than applications of 198 kg ha^{-1} and 0 kg ha^{-1} (Figure 4). Where picloram was applied at 0.14 kg ha^{-1} , fertilizer applications of 66 kg ha^{-1} provided higher juvenile spotted knapweed densities than the control which received no fertilizer. Picloram applied at 0.28 kg ha^{-1} yielded the highest densities when combined with fertilizer at 132 kg ha^{-1} , but was similar to densities with 66 kg ha^{-1} of fertilizer. Juvenile spotted knapweed density was similar among all fertilizer treatments where picloram was applied at 0.42 kg ha^{-1} .

Biomass

Biomass of spotted knapweed and grass were affected by picloram on Site 1 four years after treatment (Table 2). Spotted knapweed biomass was highest (192.1 kg ha^{-1}) where no picloram was applied ($\text{LSD}=53.9$). Picloram applied at 0.14 kg ha^{-1} resulted in spotted knapweed biomass of 49.3 kg ha^{-1} , which was similar to 10.2 and 1.9 kg ha^{-1} from

picloram applications of 0.28 and 0.42 kg ha⁻¹, respectively. Grass biomass was lowest (2248.0 kg ha⁻¹) where no picloram was applied (LSD=893.4). Grass biomass was higher in plots treated with 0.28 kg ha⁻¹ (5960.1 kg ha⁻¹), than in those treated with 0.14 kg ha⁻¹ (5057.2 kg ha⁻¹), however it was similar to those treated with 0.42 kg ha⁻¹ (5833.4 kg ha⁻¹).

Biomass of grass was also affected by grass defoliation at Site 1 (Table 2). Grass biomass was lowest in plots defoliated in all three seasons, 3939.0 kg ha⁻¹, than in all other defoliation treatments (LSD=561.1). The control (no defoliation) had the highest grass biomass of 5613.7 kg ha⁻¹, although it was similar to plots defoliated in the fall (5089.4 kg ha⁻¹).

At Site 2, picloram interacted with fertilizer to affect spotted knapweed biomass four years after treatment (Table 2). Where no picloram was applied, a fertilizer application of 132 kg ha⁻¹ provided higher spotted knapweed biomass than all other treatments (Figure 5).

Effect of fertilizer on spotted knapweed biomass was also dependent on the defoliation treatment at Site 2 (Table 2). Where no fertilizer was applied, all defoliation treatments were similar (Figure 6). Where fertilizer was applied at 66 kg ha⁻¹, defoliation in the spring resulted in the lowest spotted knapweed biomass, although it was similar to defoliation in the summer, fall, and the control. At 132 kg ha⁻¹, fertilizer interacted with defoliation in all three seasons to yield spotted knapweed biomass higher than all other defoliation treatments. Where fertilizer was applied at 180 kg ha⁻¹, all defoliation treatments yielded similar spotted knapweed biomass.

At Site 2, effect of defoliation on grass biomass was dependent on the rate of picloram applied (Table 2). When no picloram was applied, defoliation in all three seasons yielded the lowest grass biomass, although it was similar to the effect of defoliation in the summer, spring, and alternating spring/fall (Figure 7). The control, which received no defoliation, yielded the highest grass biomass and was similar to fall defoliation. When picloram was applied at 0.14 kg ha^{-1} , alternating spring/fall defoliation resulted in the highest grass biomass. However, it was similar to all treatments except summer defoliation and defoliation in all three seasons, which yielded lower biomass. At 0.28 kg ha^{-1} , picloram interacted with alternating spring/fall grass defoliation to yield grass biomass lower than plots with no defoliation. Where picloram was applied at 0.42 kg ha^{-1} , alternating spring/fall defoliation resulted in the highest grass biomass; however, this treatment was similar to summer defoliation and defoliation in the fall. Grass defoliation in the spring resulted in the lowest grass biomass, and was similar to the control and to defoliation in all three seasons.

Cover

At Site 1, picloram had the only significant effect on spotted knapweed cover four years after treatment (Table 2). Without application of picloram spotted knapweed cover (26.3%) was higher than all three picloram applications ($\text{LSD}=7.6$). Picloram applied at 0.14 kg ha^{-1} resulted spotted knapweed cover of 8.5% which was similar to applications of 0.28 kg ha^{-1} (1.6%), but was higher than applications of 0.42 kg ha^{-1} which resulted in spotted knapweed cover of (0.3%). Picloram also had the only effect on grass cover at

site 1 (Table 2). Picloram applications (0.14, 0.28, and 0.42 kg ha⁻¹) increased grass cover (23.8, 31.2, and 30.0 %, respectively) similarly over the control which was 14.9 % (LSD=8.6).

Analysis of variance showed picloram had the only affect on spotted knapweed cover at Site 2 (Table 2). All picloram treatments, 0.14, 0.28, and 0.42 kg ha⁻¹, provided lower spotted knapweed cover (3.8, 3.9, and 1.9 %) than the control, which was 25.3% (LSD=10.7).

Grass cover was affected by the interaction between picloram and fertilizer at Site 2 (Table 2). Where picloram was applied at 0.28 kg ha⁻¹, a fertilizer rate of 66 kg ha⁻¹ produced highest grass cover, however, it was similar to plots treated with picloram at 0.42 kg ha⁻¹ and fertilizer applied at 132 kg ha⁻¹ (Figure 8). Grass cover was also affected by defoliation treatments (Table 2). Plots not defoliated produced the highest grass cover (52.2%), although they were similar to those defoliated in the summer which had grass cover of 46.9% (LSD=8.0). Defoliation in all three seasons was similar to alternate spring/fall defoliation with grass covers of 33.1 and 40.0%, respectively.

Percent cover of litter at Site 1 was affected by fertilizer rate (Table 3). Fertilizer applied at 198 kg ha⁻¹ yielded a higher litter cover (43.4%) than applications of 66 and 132 kg ha⁻¹ (30.1 and 35.9 %), however, it was similar to the cover (36.3%) in plots that received no fertilizer (LSD=7.26).

Effect of defoliation on litter cover was dependent on the picloram rate (Table 3). Where no picloram was applied, plots that had not been defoliated provided higher litter cover than those defoliated alternating spring/fall and all three seasons (Figure 9). Where

picloram was applied at 0.14 kg ha^{-1} , grass defoliation in all three seasons had lower litter cover than all other defoliation treatments. At rates of 0.14 , 0.28 , and 0.42 kg ha^{-1} plots that were not clipped provided higher litter cover than all other defoliation treatments. Also, where picloram was applied at 0.28 kg ha^{-1} , defoliation in all three seasons produced lower litter cover than all other treatments except fall defoliation.

Percent cover of bare-ground at Site 1 was affected by defoliation treatments (Table 3). Plots that received no defoliation had lower bare-ground cover, 12.02%, than all other defoliation treatments, while plots that were defoliated all three seasons had the highest bare-ground cover, 40.71% (LSD=5.7). Bare-ground cover was also affected by the rate of fertilizer applied at site 1 (Table 3). Bare-ground cover was highest when 66 kg ha^{-1} of fertilizer was applied (36.5%). All other fertilizer rates (0, 132, and 198 kg ha^{-1}) resulted in similar bare-ground cover (27.8%, 27.1%, and 22.9% respectively, LSD=8.6)

Percent cover for both litter and bare-ground were affected only by defoliation at Site 2 (Table 3). Litter cover was the highest, 46.3%, in plots defoliated in the spring. All other defoliation treatments provided similar amounts of litter cover, 39.1% to 41.1% (LSD=5.0). Bare-ground cover at site 2 was lower in plots that were not defoliated, 4.5% than in any other defoliation treatments (LSD=3.7). Defoliation in all three seasons resulted in the highest cover of bare-ground, 16.3%.

Discussion

This study showed a consistent trend of increased spotted knapweed densities at fertilizer applications of 66 and 132 kg ha^{-1} over those observed at 0 or 198 kg ha^{-1} . This could be due to the fact that spotted knapweed captures available resources before

neighboring desirable species (Story et al. 1989). Adding 66 and 132 kg ha⁻¹ of fertilizer may have provided spotted knapweed nutrients needed for establishment and growth, while providing no benefit to the grasses. When 198 kg ha⁻¹ of fertilizer was applied, grasses may have been able to use the nutrients, and the competitive balance was shifted away from spotted knapweed.

Alternating spring/fall defoliation resulted in higher spotted knapweed density and biomass than annual spring or fall defoliation. Alternating spring/fall grazing is often recommended to improve range health because grasses are allowed to set seed and receive a rest period to allow seedling establishment (Rogler 1951, Johnson 1965, Frisna 1992). However, these recommendations do not take into account competition from a perennial weed. When spring defoliation directly follows fall defoliation, I believe the grasses are placed at a competitive disadvantage. Defoliation in the fall reduces the photosynthetic ability of the plant, which may reduce carbohydrate reserves (Deregibus et al. 1982). If the plants are defoliated the next spring, they may have reduced root systems and lowered carbohydrate reserves that inhibit recovery. This potentially shifts the competitive balance to spotted knapweed, allowing it to establish new seedlings which are able to outcompete the suppressed grasses. (Watson and Renny 1974, Harris and Cranston 1979, Sheley and Jacobs 1997).

Fall defoliation alone appeared to be the most appropriate defoliation treatment for minimizing spotted knapweed reinvasion after weed control. Grass and spotted knapweed biomass in fall defoliated plots were similar to the control, which received no defoliation. This was expected since grasses generally tolerate fall defoliation well. Because growth

rates are slow in the fall, removal of photosynthetic material does not draw large amounts of nutrients from the plants' reserve (McLeen and Wikeem 1985). While fall only defoliation may minimize spotted knapweed reinvasion, it may only be practical for a few livestock operations. As forage matures their nutritional quality decreases (Greene et al 1987). Thus, low protein and digestibility of fall material may not be profitable in many livestock operations.

One of the most significant results from this study was the difference between sites. Site 1, with a residual understory of smooth bromegrass and timothy, was much more responsive to the picloram treatments than Site 2, which had a residual understory dominated by Kentucky bluegrass. The Kentucky bluegrass site was generally affected more by fertilizer and defoliation treatments than Site 1. Two years after application picloram and fertilizer did not interact to affect grass yield or spotted knapweed density on either study site (Sheley and Jacobs 1997). In contrast, four years after application, picloram and fertilizer did interact to decrease spotted knapweed density at Site 2. I believe the more subtle effects of the fertilizer became evident because the effects of picloram decreased over time. The smooth bromegrass and timothy at Site 1 showed more response to applications of picloram and showed no effect from the fertilizer on spotted knapweed density, cover, or biomass even 4 years after application. Therefore I can conclude that if a residual understory of competitive, grazing tolerant grasses exists, reasonable grazing practices will not encourage spotted knapweed reinvasion. However, if poorly competitive grasses, such as Kentucky bluegrass, dominate the understory, proper grazing management is critical to prevent reinvasion of spotted knapweed.

Literature Cited

- Bedunah, D. and J. Carpenter. 1989.** Plant community response following spotted knapweed (*Centaurea maculosa* L.) control on three elk winter ranges in western Montana. In: P.K. Fay and J.R. Lacey (eds.), Knapweed Symposium Proceedings, Montana State Univ., Bozeman, MT.
- Briske, D.D. 1990.** Developmental morphology and physiology of grasses. p. 85-108. In: Grazing Management: an ecological perspective. (eds.) R.K. Heitschmidt and J.W. Stuth. Timber Press, Inc., Portland, OR. 259p.
- Chicoine, T.K. 1984.** Spotted knapweed control, seed longevity, and migration in Montana. M.S. Thesis, Montana State Univ., Bozeman, MT.
- Chicoine, E.S., P.K. Fay, and G.A. Neilsen. 1985.** Predicting weed migration from soil and climate maps. *Weed Sci.* 34:57-61.
- Cranston, R. 1988.** British Columbia Survey. Knapweed (newsletter) Vol. 2.2.
- Daubenmire, R. 1970.** Steppe vegetation of Washington. Washington Agr. Exp. Sta. Tech. Bull. No. 62.
- Davis, E.S. 1990.** Spotted knapweed (*Centaurea maculosa* L.) seed longevity, chemical control, and seed morphology. M.S. Thesis, Montana State Univ., Bozeman, MT.
- Davis, E.S., P. K. Fay, T.K. Chicoine, and C.A. Lacey. 1993.** Persistence of spotted knapweed. *Weed Sci.* 41:57-61.
- Dwyer, D.D. and J.G. Schickendanz. 1971.** Vegetation and cattle response to nitrogen fertilized rangeland in south-central New Mexico. New Mexico State Univ. Agr. Exp. Sta. Res. Rep. 215:1-5.
- Fay, P.K., E.S. Davis, T.B. Chicoine, and C.A. Lacey. 1989.** The status of long-term chemical control of spotted knapweed. In: P.K. Fay and J.R. Lacey (eds.), Knapweed Symposium Proceedings, Montana State Univ., Bozeman, MT.
- Frisna, M.R. 1991.** Elk habitat use within a rest-rotation grazing system. *Rangelands.* 14:93-96.
- Hamaker, J.W., C.R. Youngson, and G.A. Goring. 1967.** Predictions of the persistence and activity of Tordon herbicide in soils under field conditions. *Down to Earth.* 23:30-36.

- Harris, P. and R. Cranston. 1979.** An economic evaluation on control methods for diffuse and spotted knapweed in western Canada. *Can. J. Plant Sci.* 59:375-382.
- Hart, R.H., M.C. Shoop, and M.M. Ashby. 1995.** Nitrogen and atrazine on shortgrass: vegetation, cattle, and economic responses. *J. Range Manage.* 48:165-171.
- Hubbard, W.A. 1975.** Increased range forage production by reseeding and chemical control of knapweed. *J. Range Manage.* 28:406-407.
- Jacobs, J.S. and R.L. Sheley. 1997.** Relationship among Idaho fescue defoliation, soil water, and spotted knapweed emergence and growth. *J. Range Manage.* 50:258-262.
- Johnson, W.M. 1965.** Rotation, rest-rotation, and season-long grazing on a mountain range in Wyoming. USDA Forest Service. Res. Paper RM-41. 16p.
- Lacey, C.A. 1985.** A weed education program, and biology and control of spotted knapweed (*Centaurea maculosa*) in Montana. M.S. Thesis, Montana State Univ. Bozeman, MT.
- Lacey J.R., C.B. Marlow, J.R. Lane. 1989.** Influence of spotted knapweed (*Centaurea maculosa*) on surface runoff and sedimentation yield. *Weed Technol.* 3:627-631.
- Lacey, J., P. Husby, and G. Handl. 1990.** Observations on spotted and diffuse knapweed invasion into ungrazed bunchgrass communities in western Montana. *Rangelands* 12:30-32.
- Maschinski, J. and T.G. Whitman. 1989.** The continuum of plant responses to herbivory: the influence of plant association, nutrient availability, and timing. *Amer. Natur.* 134:1-19.
- McLean, A. and S. Wikeem. 1985.** Defoliation effects on three range grasses. *Rangelands* 7:61-63.
- Roché, C. 1988.** Washington Knapweed Survey. Knapweed (newsletter) Vol. 2.3.
- Rogler, G.A. 1951.** A twenty-five year comparison of continuous and rotation grazing in the Northern Plains. *J. Range Manage.* 4:35-41.
- Sheley, R.L, B.E. Olson, and L.L. Larson. 1997.** Effect of weed seed rate and grass defoliation level on diffuse knapweed. *J. Range Manage.* 50:39-43.

- Sheley, R.L. and B.F. Roché. 1982.** Rehabilitation of spotted knapweed infested rangeland in northwest Washington. Absrtact. W. Soc. Weed Sci. Denver, CO.
- Sheley, R.L., and J.S. Jacobs. 1997.** "Acceptable" levels of spotted knapweed (*Centaurea maculosa*) control. Weed Technol. 11:363-368.
- Sheley, R.L., and J.S. Jacobs. 1997.** Response of spotted knapweed and grass to picloram and fertilizer combinations. J. Range Manage. 50:263-267.
- Sheley, R.L., R.H. Callihan, and C.H. Huston. 1984.** Improvement of spotted knapweed infested pastures with picloram and fertilizer. Montana State Univ. Coop. Ext. Service Bulletin 1315. pp 21-22.
- Strang, R.M., K.M. Lindsay, R.S. Price. 1979.** Knapweeds: British Columbia's undesirable aliens. Rangelands 1:141-143.
- Tyser, R.W. and C.H. Key. 1988.** Spotted knapweed in a natural area fescue grassland: an ecological assessment. Northwest Sci. 62(4):151-166.
- Watson, A.K. and A.J. Renney. 1974.** The biology of Canadian weeds.6. *Centaurea maculosa* and *C. diffusa*. Can. J. Plant Sci. 54:687-701.

CHAPTER 3**INTEGRATING 2,4-D AND SHEEP GRAZING TO MANAGE SPOTTED
KNAPWEED INFESTED RANGELAND****Introduction**

Spotted knapweed (*Centaurea maculosa* Lam.), a native of Eurasia, is rapidly invading rangeland throughout the northwestern United States and Canada (Watson and Renney 1974, Strang et al. 1979, Harris and Cranston 1979). Spotted knapweed has been spreading at about 27% per year since 1920 and infests almost 2.2 million hectares of grassland in Montana (Chicoine et al. 1985, Lacey et al. 1989). The perennial growth habit, profuse seed production, and deep taproot of spotted knapweed enhance rapid establishment and spread (Sheley et al. 1998). Once established it is very competitive, often displacing native grasses and forbs (Davis 1990).

Spotted knapweed reduces plant species diversity (Tyser and Key 1988) and wildlife habitat (Bedunah and Carpenter 1989). Knapweed (*Centaurea* spp.) infestations also increase bare-ground (Tyser and Key 1988), surface water runoff and stream sedimentation (Lacey et al. 1989), and management costs (Griffith and Lacey 1989). However, one of the most important impacts of spotted knapweed is its reduction forage production (Watson and Renney 1974, Harris and Cranston 1979). Spotted knapweed threatens the long-term productivity of native rangelands by reducing grazing capacity by 63% on infested areas (Bucher 1984). Spotted knapweed has the potential to reduce the annual gross revenue of Montana's livestock industry by \$1.7 billion (Bucher 1984).

Most broadleaf herbicides are effective in killing spotted knapweed, but new seedlings usually emerge within a year (Lacey 1985). Two,4-D applied at 0.92 kg a.i. ha⁻¹ provided 90% control of spotted knapweed in the first year after application; however, by the second year, the control had decreased to under 40% (Fay et al. 1989). Repeated herbicide applications on large-scale infestations are rarely economically feasible (Griffith and Lacey 1989). Other management tools, such as grazing and biological controls offer promise, but in many cases need to be combined with other control methods to be effective (Sheley et al. 1996). Integrating control methods may have a synergistic effect, providing long-term sustainable spotted knapweed control and enhancing forage production on rangelands (Sheley and Roché 1982, Sheley et al. 1984, Turner 1986, Cuda et al. 1989).

Kelsey and Mihalovich (1987) showed that sheep, goat, and some cattle will ingest large quantities of fresh spotted knapweed during the spring and knapweed silage and hay during the winter. Sheep have been shown to prefer juvenile spotted knapweed plants (Olson et al. 1997). Spotted knapweed is very palatable to sheep in the spring and early summer (Cox 1989). However, as the plant matures, the concentration of cnicin, a bitter tasting sesquiterpene lactone, increases which decreases palatability (Kelsey and Mihalovich 1987). Spotted knapweed also has some nutritional value as a livestock forage with spring crude protein levels up to 18.2% (Kelsey and Mihalovich 1987).

Sheep grazing on yellow starthistle (*Centaurea solstitialis* L.) lowered seed production and canopy size and increased native plant diversity (Thomsen et al. 1993). Frequency, timing, and intensity of defoliation affect the competitive interaction between

