Spotted knapweed (Centaurea maculosa L.) control, seed longevity and migration in Montana
by Timothy Kevin Chicoine

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

Abstract:
Spotted knapweed (Centaurea maculosa L.) is an introduced perennial plant that has become a major problem. In the 60 years since its introduction into Montana, it has spread to infest over 890,000 ha. The plants' growth characteristics enable spotted knapweed to establish monoculture infestations and cause dramatic reductions in the carrying capacity of rangeland.

Field trials were established to determine the efficacy of picloram (4-amino-3,5,6-trichloropicolinic acid) and the combination of picloram and 2,4-D amine ((2,4-dichloro-phenoxy)acetic acid). Picloram applied at the rate of 0.28 kg/ha controlled spotted knapweed for up to 50 months after application, and the production of desirable forages increased by 300 to 400%. The combination of picloram + 2,4-D amine (0.14 + 2.24 kg/ha) would provide complete control of spotted knapweed 14 months after application. Picloram at the rate of 0.20 kg/ha gave the greatest increase in perennial grass production (over a 500% increase over the control) 14 months after application.

Spotted knapweed seeds remained viable after 12.5 months of burial. There were decreases in the vigor of the seedlings that could be associated with the length of time the seed was buried. The soil reserve of spotted knapweed seed was found to decrease by 72 to 81% 15 months after seed production was stopped. However, over 100 viable seeds per 0.5 m^2 remained in the reserve after this 15 month period. Based on the rate of decline witnessed in 15 months, it would take 60 to 75 months to totally exhaust the seed reserve in the soil.

A model was constructed to predict the migration of spotted knapweed in the state. Six edaphic and climatic characteristics were used to predict areas of Montana that have growing conditions similar to 116 spotted knapweed infestations obtained from a survey of 16 counties in the state. Most areas of Montana have at least one characteristic that would support the growth of the plant, and over 50% of Montana appears to have a high probability of supporting the growth of spotted knapweed. Spotted knapweed appears to favor regions where the Ponderosa pine, Douglas fir, and foothills prairie habitats are dominant.

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Master of Science

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Agronomy

MONTANA STATE UNIVERSITY
Bozeman, Montana

March 1984

APPROVAL

of a thesis submitted by

Timothy Kevin Chicoine

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

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ACKNOWLEDGMENTS

I would like to express my deepest thanks and appreciation to my advisor, Pete Fay. His continued support, encouragement, and challenges allowed me to grow and obtain a complete education.

I would also like to thank the members of my committee, Dr. John Lacey and Dr. Loren Wiesner. A special thanks is extended to Dr. G. A. Nielson for his assistance in constructing the predictive model for weed migrations.

The efforts of the members of the weed crew, Claire Barretto, Dan Burkhart, Bill Dyer, Cel Lacey, Bruce Maxwell, and Scott Nissen made it possible to complete this project.

I am especially grateful for the encouragement and support of my parents and family. A special thanks is extended to Shannon Cox, who stood by me throughout the completion of this thesis.

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ABSTRACT

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CHAPTER 1

LITERATURE REVIEW

Introduction

The knapweeds were introduced to the North American continent around the beginning of the twentieth century as contaminants of Turkistan alfalfa (Groh, 1940). They are relatively free of natural enemies. This factor, coupled with their aggressive growth habit, has enabled them to spread to infest almost 0.8 million ha in Montana (Harris and Cranston, 1979). The first recorded collection of spotted knapweed (*Centaurea maculosa* L.), the dominant species in Montana, was made in western Montana in Gallatin County in 1927. Spotted knapweed presently infests every county in the state.

The knapweeds are classified in the genus Centaurea, family Compositatae, tribe Cardueae (henceforth, the terms *C. diffusa* and diffuse knapweed *C. maculosa* and spotted knapweed will be synonymous). The genus, whose center of origin is in the Mediterranean area, is large and taxonomically complex with over 500 species.

Detrimental Aspects

Watson and Renney (1974) found no correlation between spotted knapweed infestations and soil type, however, a relationship between the degree of soil disturbance and the incidence of the knapweeds was observed. Causes of initial infestations are commonly disturbances such as roads, trails, overgrazing by livestock, and construction. Although animals will graze the rosettes and young flower heads, the spines on the flower heads, bitter taste and high fiber content of mature plants make them unpalatable to livestock.

The competitive nature of the knapweeds is well documented in a report from the Research Station at Kamloops, B.C. (Canada, Agric. Canada, 1979). They reported that bluebunch wheatgrass (*Agropyron spicatum*) growing under good rangeland condition offered little resistance to the invasion of knapweeds. In fact, the knapweeds were reported to be growing more vigorously amidst the bunchgrass than alone. The vigorous growth habit and competitive nature of the knapweeds leads to dramatic reductions in the production of desirable forage. A bluebunch wheatgrass-rough fescue (*Agropyron spicatum-Festuca scabella*) range in good condition normally produces 896 kg/ha of forage with a carrying capacity of .61 ha/ AUM. The invasion by one or more species of knapweed caused a decline from 896 to 112 kg/ha of forage and a stocking rate reduction from 0.61 to 4.8 ha/AUM (Harris and Cranston, 1979). The sharp decline in forage production is a result of the physiological and morphological characteristics of the knapweeds. The high fiber content and low palatability of the knapweeds lead to selective grazing of desirable species which further decreases the competitive ability of palatable range grasses.

Beneficial Aspects

The *Centaureas* are attractive plants during flowering. Bees readily utilize the flowers for nectar and pollen gathering. The *Centaureas* are useful for soil stabilization in disturbed areas, however, they do not permit normal plant successions to occur.

Cavallito and Bailey (1949) isolated an antibacterial principle inhibitory to *Staphylococcus aureus* and *Salmonella partyphi* from spotted knapweed. The substance, an unsaturated lactone, has the formula $C_2OH_{26}O_7$. The chemical inhibits development of resistance in bacteria by interfering with sulfhydral linkages. Spotted knapweed leaves contain approximately 1.5% of the compound on a dry weight basis.

Distinguishing Characteristics

Moore and Frankton (1974) describe the knapweeds as follows:

Centaurea diffusa Lam. Encycl. meth. 1, 675. 1783

Annual, biennial, or short-lived perennial herb to 6 cm high. Stem thin, much branched. Stiff, angled gray-green, asperous. Basal leaves deeply twice-pinnately divided to the midrib, segments remote, entire; leaves gray-green, thick and firm, asperous, lightly woolly; margins revolute. Flower heads very numerous, borne singly on the leafy-bracted, corymbosely branched stems. Flowers usually white but sometimes yellow, pink, or mauve. Head 14-16 mm high; involucre about 1 cm high, 4-5 mm broad, ellipsoid-cylindric. Outer phyllaries coniaceous, glabrous, with a waxy secretion of minute globules; ovate-spine, to 7 mm long and with also 4-5 pairs of shorter lateral spines; inner phyllaries thinner and with shorter spines or unarmed. Papus absent or short, to 1 mm.

Centaurea maculosa Lam.

Biennial, sometimes perennial herb, 2-18 cm high. Stem slender, wiry, with numerous ascending, corymbose branches each bearing a single head. Stem green, ridged, sericeous. Leaves deeply pinnately segmented to the midrib; segments remote, linear, 1-3 mm wide; lower leaves 2-3 times segmented, upper leaves once-segmented or essentially entire, linear; leaves canescent above and below, midrib prominent. Heads radiate, 16-20 mm high, 6-8 mm broad, ovoid. Phyllaries ovate to ovate-lanceolate, bearing 4-8 (rarely 12) pairs of fine stiff processes; 5-15 mm long; phyllaries menbranous, usually ribbed, usually with a dark brown or black marking at the tip and margin, glabrous marginal cilis usually dark brown and sometimes with a lighter, whitish tips. Papus white, 0.5-1.5 mm long.

Moore and Frankton (1954) investigated the possibility of interspecific hybridization among the *Centaurea* species mentioned above. Several diffuse knapweed ecotypes which possessed variation in paupal length and flower color were found to have the normal complement of chromosomes (2n = 18), a number unlike spotted knapweed (2n = 36) and Russian knapweed (*C. repens*) (2n = 26). In addition, viable pollen was found (78-98%) and they concluded that interspecific crossing does not occur.

The *Centaureas* are differentiated by the phyllaries (involucial bracts). Diffuse knapweed has a flower head covered with spines. Spotted knapweed has many rigid spines on the bracts. The upper portion of the phyllary tip of spotted knapweed is pigmented with a dark brown inverted U-shaped mark.

Seed Production

Massive seed production is a major competitive device of the knapweeds. Watson and Renney (1974) reported that diffuse knapweed produced 925 seeds per plant when grown on rangelands and 18,248 seeds when grown under irrigation. Spotted knapweed produced 436 and 25,263 seeds per plant when grown under dryland and irrigated conditions, respectively which may indicate that it is adapted to a wetter environment than diffuse knapweed. Schirman (1981) reported that diffuse knapweed is able to tolerate a drier climate than spotted knapweed. In a 3-year study, which included prolonged drought conditions, diffuse knapweed seed production was more stable than spotted knapweed. On a square meter basis, diffuse knapweed produced approximately 30,000 seeds while spotted knapweed produced more than 48,000 seeds/m^2.. The higher seed production by spotted knapweed was a result of multiple flower stem production by the plant. While there was no correlation between spotted knapweed height and the number of flower shoots or flower heads produced per plant, there was a correlation found between the number of flower heads and shoot production per plant (Story, 1976). Spotted knapweed plants produced 32 seeds per head and 29 heads per plant (approximately 1,000 seeds per plant) in Montana. If 80% seed survival is assumed (Waston and Renney, 1974; Schriman, 1981) the soil reservoir of spotted knapweed seed increases exponentially each year. The author found no reports of the longevity of viability of the seed in the soil.

Each *Centaurea* sp. has a unique method of seed dispersal. Diffuse knapweed, growing from a single stem, will break off at ground level and move in a "tumble weed" fashion permitting extensive seed dissemination. Watson and Renney (1974) described the actual seed release of diffuse knapweed:

> The achenes are individually dispersed through the small distal openings in the flower heads. Dispersal close to the parent plant is facilitated by horizontally placed involucres, which open as dehydration occurs, dropping the achenes readily.

Spotted knapweed does not disseminate its seeds over long distances since the flower stems do not tumble. The bracts of the plant open approximately 3 weeks after maturity by means of dehydration which loosens the achenes in the seed head. A flicking motion caused by plant disturbance scatters the seed for distances of up to one meter, therefore the plant does not physically disperse its seeds over great distances (Strang et al., 1979). Spotted knapweed relies on man and other animals to move it from one locality to another.

Seedling Establishment

The knapweeds are invader species which capitalize on any soil disturbance such as road construction or livestock trails. Normally a portion of the knapweed seeds germinate in the fall and the plant overwinters in the rosette stage. A second flush of seedlings typically emerge in late April to early May, before most grasses break dormancy. Schirman (1981) reported that less than 1% of the plants produce flowers in the first year of growth, so one season of rosette growth is generally required before seed production occurs. Schirman (1981) observed a correlation between the time in which growth starts in the spring, and flowering. Plants which emerged early (March through May) during the second year of growth produced flowers 70 to 95% of the time. However, if emergence was delayed until June or July, plants would not flower that season.

Spears et al. (1980) determined the optimum conditions necessary for germination. They examined canopy cover, seeding depth, and soil moisture content and found that canopy cover had no effect on germination. These results are contrary to those of Watson and Renney (1974) who found that continuous light inhibited germination of diffuse and spotted knapweed. Spears et al. (1981) accounted for the differences: ". . . either germination and emergence under field conditions is reduced by some factor other than low light intensity, or seedling survival is reduced following emergence."

The rate of seedling emergence is related to seeding depth. Spotted knapweed emerged from greater depths than diffuse knapweed. Both species had the greatest emergence rate when planted on the soil surface. Diffuse and spotted knapweed did not emerge when planted 3 to 5 cm deep, respectively. Spotted knapweed emergence decreased to 13% when planted at a depth of 3 cm. Maximum germination occurred when soil moisture was 65 to 70%. Percent germination decreased at moisture contents above and below these levels.

Spotted knapweed appears to be adapted to a wider range of environmental conditions than diffuse. Optimum temperatures for germination are 13 to 28 C for diffuse and 10 to 28 C for spotted knapweed. Temperatures lower than these delayed germination of both species. Germination of spotted knapweed was higher than diffuse at the 7 to 10 C range.

Spotted knapweed reproduces vegetatively and is classified as a short-lived perennial. Lateral shoots emerge 2.5 to 7.5 cm from the mother plant and form rosettes. Plants normally survive for 3 to 5 years which accounts, in part, for the dense stands formed by spotted knapweed. Diffuse knapweed is classified as a biennial or sometimes a triannual (Watson and Renney, 1974).

Plant Development

Spotted and diffuse knapweed bolt in May after overwintering as rosettes. Diffuse knapweed produces a single branched stem. Two year old spotted knapweed plants produce 1 to 6 stems per plant, and older plants typically produce more than a dozen branches. True stems and immature flowers are first observed in mid-June. Stems and branches elongate and flower heads continue to appear on the end of each branch throughout the summer. Flowering begins in mid-July, about two weeks earlier for spotted knapweed than for diffuse knapweed. Individual flowers remain open for 2 to 6 days. The

Centaureas are cross pollinated by insects. Mature seeds are produced 18 to 26 days after fertilization (Watson and Renney, 1974).

Diffuse and spotted knapweed are adapted to a wide range of soil types. Susceptibility to invasion is directly related to the degree of disturbance of the A horizon. However, these two species are not adapted to cultivated lands or those under irrigation. An arid period during the summer months is required by the plants (Harris and Cranston, 1979). Open habitats are preferred, although spotted knapweed will invade disturbed forest soils at relatively high altitudes.

Allelopathy

Centaurea species utilize allelopathy to maintain stand densities. Fletcher and Renney (1963) partially characterized the allelochemical as an indole. The highest concentration of the allelochemical was found in the leaves. The allelochemical extracted from infested soil caused curled and club-shaped roots of barley and tomato, results similar to the action of synthetic indole in germination tests. Diffuse knapweed was found to contain higher levels of the inhibitor on a dry weight basis than spotted knapweed.

Cultural Control

Plowing deeper than 5 cm will control diffuse and spotted knapweed (Spears et al., 1980). The land should be reseeded immediately with a vigorous grass or legume to avoid reinfestation.

Popova (1960) reported the density of diffuse knapweed increased when mowed, contrary to the findings of Watson and Renney (1974). Watson and Renney (1974) measured a reduction in seed production when plants were mowed in the flowering stage. The continued production of low growing flowering branches permitted some flowers to "escape" mowing.

Little is known about the use of burning as a means of controlling the knapweeds. The use of fire is generally discouraged since it can damage blue-bunch wheatgrass (*Agropyron spicatum*). Popova (1960) reported that diffuse knapweed was almost entirely replaced by grasses 2 years after a burn. Zednai (1968) found the germination of spotted knapweed was lowered from 68 to 3% after a burn. Strang et al. (1979) indicated that, in spite of its invasion capabilities, spotted knapweed rarely invades burned areas. Burning may be an economical method of reducing spotted and diffuse knapweed infestations on low value land.

Dodder (*Cuscuta* sp.) selectively parasitizes spotted knapweed growing among other forbs and grasses in the Bitterroot Valley of western Montana. A similar incident was reported in Bermuda where dusty miller (*Centaurea* sp.) was parasitized by dodder in a flower bed (Wang and Hughes, 1974). Haustoria attached to both leaves and stems. There was no discoloration or damage to the tissue where the haustoria entered the *Centaurea* sp., indicating a lack of resistance to the dodder.

Biological Control

Infestations of diffuse knapweed and spotted knapweed are small in Eurasia, the center of origin for the *Centaureas*, which makes it difficult to gather the natural enemies of the *Centaurea* sp. Schroeder (1977) found 82 biotic agents which attacked the *Centaureas* in Europe. Five of those agents have been released as biological control agents (Table 1) in Canada (Harris, 1979). Harris (1979) predicts that it will require a total of six agents to control the two species because of the close relationship of diffuse knapweed and spotted knapweed.

Urophora affinis, a seedhead fly, was released in Montana in 1973 (Story and Anderson, 1978). The life cycle of the insect is closely related to flower head development of the *Centaurea* sp. Peak fly activity occurs when the majority of the flower heads are 3.5 to

Table 1. The Biological Control Agents Which Have Been Released in Canada For the Control of the *Centaurea* Species (Harris, 1979).

Host Plant	Insect
Diffuse knapweed	*Sphenoptera jugoslavica* *Urophora affinis* *U. quadrifasciata*
Spotted knapweed	*Metzneria paucipunctella* *U. affinis* *U. quadrifasciata*

4.5 mm in width (Story and Anderson, 1978). Populations of the fly then decline and the last adults are observed in late July and early August. A second generation of adults emerge from late August until early September. The biological advantage to this "summer generation" is limited since flowers are not at the proper stage of development for oviposition. *Urophora* are weak fliers which rarely travel more than 1 meter at a time. They usually visit the top 5 to 6 flower branches of the plant and the amount of time spent on each flower is dependent upon the time of day (Story, 1976).

Myers and Harris (1980) differentiated *U. affinis* from *U. quadrifasciata* by the following criteria:

1. *U. quadrifasciata* had an obligatory second generation whereas 10 to 30% of the first generation of *U. affinis* will emerge to produce a second generation.
2. *U. quadrifasciata* lay eggs slightly later than *U. affinis* and chose larger buds for oviposition.
3. The galls formed by *U. quadrifasciata* have thin walls in comparison to the galls formed by *U. affinis* therefore less energy is expended by the infested host plant.

Myers and Harris (1980) analyzed interspecific competition between *U. affinis* and *U. quadrifasciata*. When both insects infested one plant the larval density of each species was reduced, however, the total fly density in the knapweed infestation was higher. Seed destruction was greater with both species present because the number of attacks per plant was increased by the different rates of development of the two species.

U. quadrifasciata adults bridged the gap between the two *U. affinis* generations. Adult life lasts approximately 3 weeks for both species.

Zwolfer (1970) described the damage caused by the fly as "... a destruction of the achenes and deformation of the receptacle of the capitulum which leads to a reduction of the production of viable seeds."

The *Urophora* sp. is not without enemies. Story (1976) reports a predatory spider (*Dictuna major*) which caused reductions in *Urophora* populations.

The amount of seed destruction caused by the *Urophora* sp. at the Regina Research Station in Regina (1976-1978) was greater on spotted knapweed than on diffuse. There were 1.2 to 1.8 galls per head on diffuse knapweed and 3.4 to 5.0 galls per head on spotted, while plant dry weight and seed production were reduced 74 and 95%, respectively. Infested diffuse knapweed plants still produced more than 1500 viable seeds per plant.

Metzneria paucipunctella introduction has been described by Dunn (1978). This insect (a small gelechild moth) is having difficulty overwintering in certain parts of Canada.

Watson et al. (1981) and Savile (1973, 1970, 1970a) describe two rust fungi, *Puccinia centaureae* and *P. jaceae* on diffuse knapweed. Watson et al. (1981) tested more than 70 strains of the rust collected in Bulgaria and Rumania and found that at least 10 of the strains were virulent on Canadian strains of diffuse knapweed. The *Puccinia* sp. are presently in the final stages of the screening tests and release is expected shortly.

Watson et al. (1974) observed wilting of diffuse knapweed in the bud stage, and isolated sclerotia from within the root tissues and surfaces of the lower stems and basal leaves. *Sclerotinia sclerotiorum* and *Microspaeropsis centaureae* (Morgan-Jones, 1974) were isolated from the infested tissues. Plants inoculated with *S. sclerotiorum* developed typical symptoms 10 days after infection. Seedlings and rosettes suffered complete leaf loss, however, mature plants produced symptoms only on the basal leaves. Sclerotia were found within the root crowns and re-isolated to the introduced organism. No symptoms were observed on spotted knapweed inoculated with *S. sclerotiorum*. *M. centaureae* killed diffuse knapweed seedlings in 2 weeks and necrotic lesions appeared on rosette plants in 4 weeks. The circular lesions had tan colored centers with purplish-brown margins and were up to 8 cm in diameter. Similar symptoms occurred on spotted knapweed.

Sphenoptera jugoslavica, a member of the *Coleoptera* family, is a root-feeding larvae that has been released in Canada. Adults feed on the rosette leaves. Another root-feeding moth, *Pterolonche* sp., is being screened for release. This moth will not compete with *S. jugoslavica* since it feeds of the outside of the roots. These two organisms should be compatible on diffuse knapweed, however, activity on spotted knapweed will be limited due to the absence of a taproot (Myers, 1977).

Chemical Control

Chemical control of the *Centaurea* sp. was limited to the use of 2,4-D ((2,4-dichlorophenoxy)acetic acid) and soil sterilants during the early 1960s. Two,4-D applied at the proper growth stage provides adequate control of spotted and diffuse knapweed. Seedlings are more sensitive than rosettes. Applications should be made when the seedlings are 5 to 8 cm tall and growing conditions are favorable. Seedling emergence throughout the growing season complicates treating the plant at the proper stage. Several annual applications would be required to treat the seedlings in the proper stage of growth because of the short residual activity of 2,4-D. Rates of 1.12 to 2.24 kg/ha of active ingredient of 2,4-D applied in late May to early June when bolted plants are 15 to 20 cm tall will provide at least 80% control that year. Seed production will be nearly eliminated during the treatment year. Reapplications will be necessary in following years (Belles et al., 1980a, 1980b;

Renney and Hughes, 1969; Wattenbarger et al., 1980). The ester formulation of 2,4-D is more effective than the amine formulation (Belles et al., 1978).

The discovery of picloram (4-amino-3,5,6-trichloropicolinic acid) made it possible to have selective residual activity against broadleaf plants with little damage to grass species. Early work with picloram (Renney and Hughes, 1969) showed that 0.42 to 0.56 kg/ha provided optimum control of *Centaurea* species. When 0.56 kg/ha was applied in July there was 100% control one year later. There was no difference in spotted knapweed control from applications made during May to July, and residual activity provided satisfactory control for at least 2 years. There was a 49% increase in grass cover (*Agropyron spicatum, Festuca* sp., *Stipa comata, Koelaria cristata, Poa pratensis*, and *Poa secunda*) one year after an application of 0.56 kg/ha in picloram (Renney and Hughes, 1969).

Picloram is not toxic to grazing animals. Lynn (1965) reports an LD_{50} of 10,330 mg/kg for the adult male white rat. Picloram was fed to sheep and cattle at 4,650 mg/kg and 3,480 mg/kg with no ill effects. Levels of up to 100 parts per million in water produced no ill effects to several species of fish, including brook, brown, and rainbow trout.

Schifres and Halifax (1972) tested the effect of picloram on the germination and development of range grasses. Picloram at 125 parts per million did not affect the germination of *Buchloe dactyloides, Bouteloua curtipendula*, and *Panicum virgatum*, however, radicle elongation was reduced by 125 parts per billion of picloram. Shoot elongation was not reduced until the concentration of picloram reached 1000 ppb. They concluded that field rates of picloram would not be harmful to the above-mentioned species.

Arnold and Santelman (1966) reported that 0.84, 1.68, and 3.36 kg/ha of picloram applied pre-emergence prevented the germination of sideoats gramma (*Bouteloua curtipendula*), big bluestem (*Andropogon gerardi*), and blue gramma (*Bouteloua gracilis*). Greenhouse plants in the 4-leaf stage were not injured by 0.84 kg/ha of picloram. However, in a field trial, all species were injured by all rates of picloram when treated in the 2 and 4 leaf stages. When treated at the 6 leaf stage only the *Bouteloua* sp. were damaged by the highest rate of picloram tested. A trend toward the selection of the less desirable grass and forb species was noticed in an established rangeland community when it was treated with 1.12, 2.24, and 4.48 kg/ha of picloram. These tests did not include any of the lower rates of picloram recommended for use in controlling spotted and diffuse knapweed.

Twenty-five ppm of picloram was detected in buffalograss (*Buchloe dactyloides*) and blue gramma (*Bouteloua gracilis*) tissue immediately following the application of 0.28 kg/ha of picloram (Schifres et al., 1971b). This decreased to less than 1 ppm in the tissue 30 to 60 days following treatment, a drop of 93%. Flushes of growth temporarily increased the amount of picloram in the tissues due to increased root uptake of soil solutions at the time of growth.

Goring and Haymaker (1971) reported that picloram is metabolized in plants, by soil microorganisms, and by sunlight in water. Increasing rates of picloram in soil increases the rate of degradation. The breakdown rate also increases with increases in soil organic matter content, temperature, and moisture. Increases in pH, organic matter and levels of hydrated iron and aluminum oxide in the soil increases the residual period. Picloram leached to a maximum of 30 to 61 cm in heavy soil and 61 to 122 cm in sandy soil which received 102 to 127 cm of rainfall annually. Haymaker, Youngson, and Goring (1967) determined half-order constants that were correlated with the number of days over 32 C.

Merkle et al. (1967) found only 25 and 15% of the picloram applied was detectable one year after treatment with 0.48 and 2.24 kg/ha, respectively, in a greenhouse study. The chemical is reported to be broken down by ultraviolet light.

Schifres et al. (1971a) found that 0.28 kg/ha of picloram + 0.28 kg/ha of 2,4,5-T ((2,4,5-trichlorophenoxy)acetic acid) dissipated from the soil within 90 days under the warm, dry conditions found in semiarid grasslands. The amount of picloram in the top

2.5 cm of soil was reduced 85% 10 days after application, probably due to breakdown by ultraviolet light. Leaching was generally confined to the top 30 cm of the soil.

Belles et al. (1980) tested the effect of combining fertilizer and picloram on the control of spotted knapweed. Picloram alone (at rate of 0.28 and 0.56 kg/ha) and in combination with 2,4-D amine (at picloram + 2,4-D rates of 0.14 + 0.28 kg/ha and 0.28 kg/ha + 0.56 kg/ha, respectively) gave the best control of spotted knapweed 2 years after application. One year after herbicide application one half of each plot was treated with ammonium sulfate (45 kg/ha of N). When spotted knapweed was not adequately controlled, it was able to outcompete the forage species for the added nitrogen. In the unsprayed check spotted knapweed dry weight increased 1.5 times in response to the nitrogen with no increases in desirable forage production. No herbicide-fertilizer interactions were evident.

Hubbard (1975) controlled spotted knapweed with 0.28 kg/ha of picloram and seeded *Agropyron cristatum* (8.87 kg of seed per ha) with a rangeland drill. Forage dry matter production increased 32% one year following treatment. There was an 82% increase in forage production after 4 years. Plots which were seeded but unsprayed also had a significant increase in forage production. Treatment with 0.28 kg/ha gave a greater increase in forage production than 0.56 kg/ha of picloram. Restriction of grazing after treatment is necessary to allow the grass time to become established.

Maddox (1979) calculated that the cost of treating all hectares infested with spotted and diffuse knapweed in North America (at $37/ha) would exceed $54 million.

Glyphosate (N-(phosphonomethyl) glycine) provided 50 to 70% control of spotted and diffuse knapweed when the plants were sprayed in the rosette to early bolting stage. Control levels were sharply reduced the following season. Glyphosate had little effect on plants treated in the late bloom stage (Belles et al., 1978).

Factors Which Hinder Chemical Control

Leaf pubescence and the distribution and size of the stomates affect the uptake and translocation of foliar sprays. Ormrod and Renney (1968) measured the number of stomata and length of guard cells in diffuse and spotted knapweed (Table 2), and concluded that diffuse knapweed may survive in dried, warmer climates than spotted knapweed since a larger percentage of its stomata are located on the lower surface of the leaves.

Table 2. The Number of Stomata, and Length of Guard Cells in Diffuse and Spotted Knapweed.

	Number of Stomates/mm^2		Length of Guard Cells
	Upper Surface	Lower Surface	(μ)
Diffuse knapweed	143 ± 53	167 ± 49	28 + 5
Spotted knapweed	143 ± 28	140 ± 34	29 + 6

While the trichomes of diffuse knapweed and spotted knapweed are nearly identical, the trichomes of diffuse knapweed have a gland at the tip (Ormrod and Renney, 1968). Watson and Renney (1974) hypothesized that the trichomes interfere with herbicide penetration into the leaf surface and that higher doses of chemicals are needed for equivilent control.

The accessory cells of diffuse knapweed tended to be arranged in a diacytic pattern while those of spotted knapweed are in an anisocytic pattern. The epidermal cells near the base of the trichomes on spotted knapweed had thickened walls (Ormord and Renney, 1968).

Summary

The effect of spotted and diffuse knapweed invasion on rangeland can be disasterous since the use of allelochemicals and a competitive growth habit can lead to monoculture infestations in rangeland that is in good condition. Although the knapweeds reproduce mainly by seed, little is known about the longevity of the seed reserves in the soil.

The usefulness of cultural methods for control of the knapweeds is limited. Deep plowing and reseeding with competitive grasses and legumes will eliminate some knapweed problems, but most of the land infested by these plants is not suitable for cultivation. Little is known about the effects of burning on spotted or diffuse knapweed. The detrimental effects of a hot, fall fire on the bunchgrasses that seem to be most susceptible to knapweed invasion rule out fall burning as a method of controlling the knapweeds.

Biological control is being developed, but it will take many years before an effective program is in effect. One insect, *Urophora affinis*, has established itself on the knapweeds, but approximately five more agents are needed before an effective biological control program will be working.

Herbicides are an effective means of controlling spotted and diffuse knapweed. Picloram, 2,4-D, dicamba, and MCPA will effectively control the knapweeds. The residual aspects of picloram and tolerance of most grass species make picloram an attractive means of reducing the rate of spread of spotted and diffuse knapweed.

CHAPTER 2

CONTROL OF SPOTTED KNAPWEED WITH PICLORAM AND PICLORAM-2,4-D COMBINATIONS

Abstract

Control of spotted knapweed (*Centaurea maculosa* Lam.) with picloram (4-amino-3,5,6-trichloropicolnic acid) was measured at several locations in Montana. The residual activity of 0.28 kg/ha picloram provided 88% reduction in mature plant density 51 months after application. The production of perennial grass herbage increased 200 to 500% following elimination of spotted knapweed. The increase in grass production was lost when the treated plots had a mature plant density that was only 12% of the control. Increasing rates of picloram from 0.07 to 0.28 kg/ha gave excellent control of spotted knapweed plants 14 months after application. The lower rates of picloram were more effective when combined with applications of 2,4-D amine. Mature and seedling spotted knapweed plants were partially controlled 14 months after application with low (0.07 kg/ha) rates of picloram. The most effective treatment to control spotted knapweed and increase perennial grass production 14 months after application was 0.21 kg/ha of picloram applied alone or in combination with 2,4-D amine.

Introduction

Spotted knapweed (*Centaurea maculosa* Lam.) is an introduced perennial which has spread to infest 0.8 million hectares since its introduction into Montana 60 years ago (Forcella and Harvey, 1981). The plant can reduce the livestock carrying capacity of rangeland by as much as 70% (Harris and Cranston, 1979).

Picloram (4-amino-3,5,6-trichloropicolinic acid) provides excellent control of spotted knapweed for 2 to 3 years when applied at the rate of 0.28 to 1.12 kg/ha (Belles et al., 1980 and 1978; Harris, 1979). The long term control of spotted knapweed provided by 0.28 kg/ha of picloram extends beyond the predicted length of residual activity for the herbicide. Haymaker et al. (1967) reported that 90% of the 0.28 kg/ha rate of picloram will dissipate in approximately 12.4 months, therefore no more than 0.03 kg/ha would remain in the soil the second and third year after application.

Two field experiments were initiated to determine the percent and longevity of control of spotted knapweed control by picloram alone, and in combination with 2,4-D amine ((2,4-dichlorophenoxy) acetic acid).

Materials and Methods

Field studies were established in 1979 by Professor Emeritus L. O. Baker, Plant and Soil Science Department, Montana State University to determine the optimum time of treatment for control of spotted knapweed. Treatments included 2,4-D amine (((2,4-dichlorophenoxy) acetic acid) (2.24 kg/ha), 2,4-D amine + picloram (4-amino-3,5,6-trichloropicolinic acid) 2.24 + 0.28 kg/ha and 1.12 + 0.28 kg/ha), picloram (0.28 kg/ha), 2,4-D amine + dicamba (3,6-dichloro-o-anisic acid) (1.12 + 0.56 kg/ha), and MCPA (2-methyl-4chlorophenoxyacetic acid) (2.24 kg/ha). Applications were made in mid-May, and mid- to late June. Herbicides were applied in 187 liters of water per ha with a CO_2 pressurized backpack sprayer. The 2.44 X 7.62 m plots were arranged in a randomized complete block design with 3 replications at each location. The study was established at Harlowton (river bottom pasture receiving 36 cm of annual precipitation), Ovando (abandoned hay land, receiving 45 cm of annual precipitation), and Stevensville (abandoned crop land receiving 41 cm of annual precipitation), Montana. Grass species present were smooth bromegrass (*Bromus inermis*), western wheatgrass (*Agropyron smithi*), timothy (*Phleum* *pratense*), needleandthread grass (*Stipa comata*), blue grama (*Bouteloua gracilis*) and an unidentified *Poa* spp. All locations had gravelly, well drained Haploboroll soils. Complete soil information from Harlowton and Ovando is given in Appendix Table 31.

A second field trial was established in June, 1982 to determine the efficacy of picloram at rates below 0.28 kg/ha alone and in combination with 2,4-D amine on spotted knapweed. Picloram was applied at 0, 0.07, 0.11, 0.14, 0.21, 0.22, 0.25, and 0.28 kg/ha in 137 l/ha of water using a CO_2 pressurized backpack sprayer. Plots (3.4 X 12.2 m) were arranged in a split block design with 3 replications. Two,4-D was applied at 2.24 kg/ha as the main plot treatment, and the picloram rates applied as the subplot treatments. Individual plots were spatially separated from each other by a 2.13 m buffer zone which was treated with picloram + 2,4-D amine (0.37 + 2.24 kg/ha) to minimize contamination from spotted knapweed seed production in neighboring plots. The entire boundary of the experimental area was further separated by a buffer zone 3.35 m wide which was sprayed with the same mixture of picloram and 2,4-D amine. The experiment was established at the 3 locations described above.

Prior to herbicide application, spotted knapweed plant density in each 41.5 m^2 plot was determined by counting the number of plants in two randomly selected 0.09 m^2 areas per plot. A list of the common plant species at each experimental location is given in the Appendix (Table 32).

In June, 1980 the number of mature plants were counted in each plot at Ovando and Stevensville. The amount of seedling regrowth was also rated using a scale of 1 to 4 (1-no seedlings present; 4-150 seedlings or more per 0.09 m^2). Stand densities were taken in three randomly selected areas (0.09 m^2) per subplot in June and August each year. Herbage production was determined during the 1980-1982 period by clipping three random 0.09 m^2 areas of each subplot. Two 0.5 m^2 areas were clipped in 1983 in an attempt to reduce the variability in the herbage production data. The annual clipping data was collected around the first week of August by cutting the vegetation to crown height with a hand clipper. Growth from previous seasons was discarded.

Data was collected from only Ovando and Stevensville in June, 1980, and only at Harlowton in 1981. The Stevensville location was cultivated in the spring of 1983, preventing further data collection from that location.

The statistical analysis used for the Baker experiment was a two-way analysis of variance. A two-way analysis of variance for a split-plot design was used for statistical summarization of the picloram rate study.

Results and Discussion

The Baker Experiment

Visual ratings were taken during the first week of August, 1979 to determine the effect of herbicide application on spotted knapweed control. All treatments applied in late May (after the plants had emerged from overwintering) gave at least 70% control of spotted knapweed when averaged across locations in the season of application (Table 3).

The variation in control among identical treatments at different locations may have been caused by phenological differences in the spotted knapweed plants at the time of application. Seedling emergence may not have been complete when treatments were made on 5-21-79 at Harlowton, while at Stevensville and Ovando emergence was complete. The only treatments which provided 70% or greater control two months after application at Harlowton contained picloram.

Thirteen months after application, the MCPA, 2,4-D amine, and 2,4-D-dicamba treatments failed to provide complete control of spotted knapweed (Table 4). Applications of 2,4-D amine on 5-21-79 at Stevensville provided slightly better suppression of mature

Table 3. Percent Control of Spotted Knapweed Two and One Half Months After Herbicide Application.*

Herbicide Treatment	Rate (kg/ha)	Percent Control of Spotted Knapweed			
		Harlowton	Ovando	Stevensville	$\bar{X}$
2,4-D amine	2.24	30	92	100	74
2,4-D amine + picloram	2.24 0.28	70	93	100	87
2,4-D amine + picloram	1.12 0.28	100	85	100	95
picloram	0.28	100	91	100	97
2,4-D amine + dicamba	1.12 0.56	50	91	100	80
MCPA	2.24	50	85	83	73
Control	——	0	0	0	0
LSD.05	——	48	15	20	40
C.V.%	——	47	11	13	22

*Treatments were applied on 5-16, 5-22, and 5-21-79 at Harlowton, Ovando, and Stevensville, respectively.

plants one year after treatment than did treatments made at Ovando. A possible explanation for this is that the plants capable of developing in that season had emerged by the time treatments were applied. The presence of established seedlings indicates that no residual herbicide activity exists for these treatments one year after application. Picloram suppressed both mature and seedling growth one year after application at all locations that were rated.

Herbage production data collected in late July, 1980 indicated that spotted knapweed was not present in any plot treated with picloram (Table 5). There was no difference in the average spotted knapweed production between plots treated with 2,4-D amine and the untreated control plots one year after application (Table 5). Spotted knapweed production increased on plots treated with 2,4-D amine to levels greater than on untreated plots at Harlowton because a few large plants were produced in each plot. Grass production was increased on all treated plots to levels significantly greater than the control. Picloram treat-

Table 4. Visual Ratings Made on June 5, 1980 of Herbicide Treatments Applied on 3 Dates in 1979 for Spotted Knapweed Control at Stevensville and Ovando.**

Herbicide Treatment	Rate (kg/ha)	Date of Treatment	No. of Mature Plants per Plot		Seedling Rating	
			Ovando	Stevensville	Ovando	Stevensville
2,4-D amine	2.24	5-17-79	53	*	3.3	*
2,4-D amine + picloram	2.24 0.28	5-17-79	0	*	1	*
2,4-D amine + dicamba	1.12 0.56	5-17-79	38	*	2.0	*
2,4-D amine	2.24	5-21-79	48	0	1.0	3.3
2,4-D amine + picloram	2.24 0.28	5-21-79	0	0	1	1.7
2,4-D amine + picloram	1.12 0.28	5-21-79	0	0	1.0	1.7
2,4-D amine + dicamba	1.12 0.56	5-21-79	30	5	1.7	1.0
picloram	0.28	5-21-79	0	0	1.0	1.7
MCPA	2.24	5-21-79	77	5	2.7	4.0
2,4-D amine	2.24	6-13-79	57	2	3.3	3.3
2,4-D amine + picloram	2.24 0.28	6-13-79	1	0	1.0	1.7
picloram	0.28	6-13-79	0	0	1.0	1.7
Control	——	——	150	60	4.0	4.0
LSD.05			68	25	1.1	1.3

*Treatment not applied.
**Actual dates of treatment: Ovando 5-17, 5-22, and 6-25-79; Stevensville 5-25 and 6-25-79.

ments, when averaged across locations, had a four-fold increase in grass production over the untreated areas.

Visual ratings, taken in the third week of October, 1981, at Harlowton indicated that treatments containing picloram continued to suppress mature plant and seedling growth of spotted knapweed 3 seasons after application (Table 6). The decrease in seedling control indicates a reduction of picloram residues.

Picloram continued to give 100% control of mature and immature spotted knapweed plants at Ovando, and 93 to 100% control at Stevensville 38 months after application

Table 5. Spotted Knapweed and Grass Production on July 30, 1980, Two Seasons After Herbicide Treatment at Harlowton, Ovando, and Stevensville.*

Herbicide Treatment	Rate (kg/ha)	Harlowton	Ovando	Stevensville	$\bar{X}$
		Herbage Production (Kg/ha)			
2,4-D amine	2.24				
spotted knapweed		168.2	93.1	26.9	96.1
grass		976.0	1342.0	2304.0	1541.0
2,4-D amine	2.24				
+ picloram	0.28				
spotted knapweed		0.0	0.0	0.0	0.0
grass		1716.6	1723.0	2554.0	2001.0
picloram	0.28				
spotted knapweed		0.0	0.0	0.0	0.0
grass		2200.0	1952.4	2378.0	2177.0
Control					
spotted knapweed		120.3	205.4	120.2	148.4
grass		299.6	286.8	839.0	475.1
LSD.05					
spotted knapweed		41.0	105.1	26.7	104.9
grass		1644.8	902.8	1212.2	594.1

*Only plots treated on 5-21-79 were clipped.

Table 6. Spotted Knapweed Control at Harlowton 29 Months After Herbicide Application.*

Herbicide Treatment	Rate (kg/ha)	Date of Treatment	Percent Control of Mature Plants	Seedlings
2,4-D amine	2.24	5-17-79	29	23
2,4-D amine + picloram	2.24 .28	5-17-79	96	94
2,4-D amine	2.24	5-22-79	32	22
2,4-D amine + picloram	2.24 .28	5-22-79	98	79
picloram	.28	5-22-79	98	91
MCPA	2.24	5-22-79	20	8
2,4-D amine + dicamba	1.12 .56	5-22-79	17	14
2,4-D amine + picloram	1.12 .28	5-22-79	98	75
2,4-D amine	2.24	6-13-79	60	45
2,4-D amine + picloram	2.24 .28	6-13-79	95	84
Control	–	––	0	0
LSD.05			27	29

*Plots were visually rated on 10-22-81.

(Table 7). There was a decrease in the control of spotted knapweed based on mature plant density from 1981 to 1983 on plots treated with picloram at Harlowton. Control averaged 97% in 1981, 94.5% in 1982, and 88% in 1983, 29, 38, and 50 months after application, respectively (Tables 6, 7, and 9). This slight decrease in control from 29 to 50 months after application could be caused by the gradual degradation of picloram. Residual control of seedling growth did not change from 29 to 38 months after the application of picloram (Tables 6 and 7). The seedling growth in 1981 (29 months after picloram application) did not cause a marked increase in the density of mature spotted knapweed plants in 1982 (38 months after application). There are two possible explanations for the lack of establishment. Picloram residues from an application of 0.28 kg/ha may be sufficient to control seedling establishment, thus preventing them from becoming mature plants. Picloram residues from an application of 0.28 kg/ha however, appears to be too low to control mature plant growth or seed production 29 months after application. The increase in grass cover seen when the allelopathic influence of spotted knapweed (Fletcher and Renney, 1963) is removed could also prevent seedlings from becoming mature plants by not allowing seedlings to establish themselves.

Herbage production data collected in 1982 indicated that picloram reduced spotted knapweed production by at least 90% 38 months after application. Forage production was increased 200 to 630% on plots treated with picloram in 1979 (Table 8).

Picloram continued to give at least 98% reduction in stand density of mature spotted knapweed plants 50 months (1983) after application at Ovando (Table 9). Control of mature spotted knapweed plants had dropped from 100% to 88% 50 months after the application of picloram at Harlowton.

The density of mature spotted knapweed plants in plots treated with picloram was still less than the control plots 50 months after application at Harlowton and Ovando (Table 9). Perennial grass production was 200 to 380% higher and spotted knapweed herb-

Table 7. Spotted Knapweed Stand Densities on August 4, 1982, 38 Months After Treatment at Harlowton, Ovando, and Stevensville.

Herbicide Treatment	Rate (kg/ha)	Date of Treatment	Number of Mature Plants and Immature Plants per 0.5 meter^2			
			Harlowton	Ovando	Stevensville	$\bar{X}$
2,4-D amine	2.24					
+ picloram	0.28	5-21-79				
mature			3.0	0.0	0.6	1.2
immature			64.9	0.0	2.3	22.4
2,4-D amine	1.12					
+ picloram	0.28	5-21-79				
mature			1.1	0.0	0.6	0.6
immature			49.1	0.0	1.1	16.7
picloram	0.28	5-21-79				
mature			5.2	0.0	1.6	2.3
immature			66.2	0.0	4.4	23.5
2,4-D amine	2.24					
+ picloram	0.28	6-13-79				
mature			1.6	0.0	0.0	0.5
immature			65.1	0.0	2.2	22.4
Control	—					
mature			47.2	46.6	24.0	39.3
immature			513.6	679.2	72.1	421.6
LSD.05						
mature			2.4	3.4	2.2	13.1
immature			79.3	203.2	12.6	309.1

Table 8. Herbage Production on August 4, 1982, 38 Months After Herbicide Treatment for Spotted Knapweed Control at Harlowton, Ovando, and Stevensville.

			Spotted Knapweed and Perennial Grass			
Herbicide Treatment	Rate (kg/ha)	Date of Treatment	Harlowton	Ovando	Stevensville	$\overline{X}$
				Herbage (Kg/ha)		
2,4-D amine	2.24					
+ picloram	0.28	5-21-79				
spotted knapweed			223.8	0.0	37.9	87.3
perennial grass			2155.4	1758.1	1272.2	1729.0
2,4-D amine	1.12					
+ picloram	0.28	5-21-79				
spotted knapweed			217.8	0.0	135.8	117.9
perennial grass			1314.9	1746.4	821.2	1294.2
picloram	0.28	5-21-79				
spotted knapweed			73.4	0.0	25.9	33.1
perennial grass			1938.8	1732.2	1393.4	1688.1
2,4-D amine	2.24					
+ picloram	0.28	6-13-79				
spotted knapweed			108.4	0.0	13.3	40.6
perennial grass			1755.4	1853.4	1282.2	1664.3
Control	–					
spotted knapweed			2100.5	3264.3	2470.6	2611.8
perennial grass			433.3	253.2	177.6	288.0
LSD.05						
spotted knapweed			277.2	727.6	252.0	677.7
perennial grass			125.6	148.9	177.6	463.1

Table 9. Spotted Knapweed Density on July 29 and 30, 1983, 50 Months After Herbicide Application at Harlowton and Ovando.

			No. of Mature Plants per 0.5 meter^2		
Herbicide Treatment	Rate (kg/ha)	Date of Treatment	Harlowton	Ovando	$\overline{X}$
2,4-D amine	2.24				
+ picloram	0.28	5-21-79	8.0	0.9	4.5
picloram	0.28	5-21-79	9.0	0.0	4.5
2,4-D amine	1.12				
+ picloram	0.28	5-21-79	6.3	0.6	3.5
2,4-D amine	2.24				
+ picloram	0.28	6-13-79	7.7	1.0	4.4
Control	–		64.6	57.3	61.0
LSD.05			17.3	5.2	3.0
C.V.%			48.1	23.8	5.1

age reduced by 96% or more at Ovando in 1983 when compared to untreated plots (Table 10). Picloram reduced the density and herbage production of mature spotted knapweed plants by 88 and 45%, respectively, 50 months after application at Harlowton. However, the slight reinfestation had a dramatic effect on the production of perennial grasses. The allelopathic influence of the reestablished spotted knapweed plants (Fletcher and Renney, 1963) reduced the production of perennial grass to the point where only the treatment made on 6-13-79 had greater perennial grass production than the untreated control (Table 10).

Table 10. Spotted Knapweed and Perennial Grass Herbage Production on July 29 and 30, 1983, 50 Months After Herbicide Application at Harlowton and Ovando.

Herbicide Treatment	Rate (kg/ha)	Date of Treatment	Spotted Knapweed and Perennial Grass		
			Harlowton	Ovando	$\bar{X}$
			Herbage Production (Kg/ha)		
2,4-D amine	2.24				
+ picloram	0.28	5-21-79			
spotted knapweed			728.4	39.8	384.4
perennial grass			931.2	1352.2	1142.7
2,4-D amine	1.12				
+ picloram	0.28	5-21-79			
spotted knapweed			621.8	0.9	311.4
perennial grass			486.2	1558.8	1022.5
picloram	0.28	5-21-79			
spotted knapweed			845.8	52.7	449.3
perennial grass			885.4	1552.4	1218.9
2,4-D amine	2.28				
+ picloram	0.28	6-13-79			
spotted knapweed			745.4	50.1	347.8
perennial grass			1166.8	1468.8	1317.8
Control	–				
spotted knapweed			1280.2	965.1	1122.7
perennial grass			100.7	319.0	209.9
LSD.05					
spotted knapweed			463.6	169.0	440.0
perennial grass			1005.2	596.0	850.7
C.V.%.			28.4	31.4	
			57.3	22.3	

Several factors probably influenced the rate of spotted knapweed reinfestation of picloram treated plots at Harlowton. The annual use of the test site as an early spring cattle pasture may have accelerated reinfestation by overgrazing since the treated areas provided the only significant amount of forage in the pasture. Climatic differences between Harlowton and Ovando from 1979 and 1983 (Appendix Table 33) may play a major role in the degradation of picloram, and thus the degree of residual activity seen 50 months after the application of 0.28 kg/ha. A major climatic difference between Harlowton and Ovando is the number of days the ground is covered with snow. Work by Schifres et al. (1971) indicates that 85% of an application of 0.28 kg/ha picloram is found in the top 2.5 cm of soil, and is quickly dissipated, probably as a result of breakdown by ultra-violet light. The longer period of snow cover and cooler temperatures at Ovando would slow down the rate of microbial and ultra-violet breakdown of picloram (Goring and Haymaker, 1971) and give a longer period of residual activity.

The different grass species which established in the plots at Ovando and Harlowton may also have had an effect on spotted knapweed reinfestation. Smooth bromegrass, western wheatgrass, and timothy were the main species at Ovando, while Harlowton was dominated by a bluegrass, western wheatgrass, blue grama, and needleandthread grass. The different sod forming capabilities of the species may have influenced the ability of spotted knapweed seedlings to establish and become mature plants.

Picloram Rate Study

The short term effects of picloram on spotted knapweed control and forage production was measured by clipping in early August, 1982 (Tables 11 and 12). Two months after herbicide application the reduction in spotted knapweed herbage production tended to be directly related to the rate of picloram applied. When treatment included 2,4-D amine, further reductions in spotted knapweed herbage was measured. There was no increase in perennial grass or total forage production at any location in the year of treatment (Table 12).

Picloram rates as low as 0.14 kg/ha provided excellent control of mature spotted knapweed plants 12 and 14 months after application (Table 13). The density of spotted knapweed plants was further reduced when 2,4-D amine was applied with picloram. The density of immature plants declined in late July when compared to the population in June at Harlowton (Table 14). By late July the seedlings were no longer dependent upon cotyledonary reserves and were actively absorbing lethal levels of picloram from the soil solution.

There was no difference in the density of mature spotted knapweed plants between untreated plots and in plots treated with 0.07 kg/ha of picloram, however, the sprayed plants were stunted. The average plant height was reduced from 36.5 mm in the control to 16.8 mm in treated plots in June 1983. Dry weight was reduced from 600 to 211 mg per plant. This decrease in biomass was still apparent in the production data taken in late July (Table 15). The plants treated with 0.07 kg/ha of picloram had an average weight of 139 mg compared to 1394 mg for untreated plants.

Perennial grass production was increased more than 96% 14 months after application of 2,4-D amine alone (Table 16). The inclusion of 0.07 kg/ha of picloram with the 2,4-D treatment increased grass production 300 to 400% over untreated areas, an increase achieved without complete suppression of spotted knapweed growth. When spotted knapweed growth was completely suppressed perennial grass production increased as much as 517%. The inclusion of 2.24 kg/ha of 2,4-D amine with any of the picloram treatments did not have a significant impact on the increase in grass production 14 months after application. The residual activity of picloram continued to suppress spotted knapweed growth and resulted in a more complete release of perennial grass growth, possibly due to the elimination of the allelopathic influence of spotted knapweed (Fletcher and Renney, 1963). This

Table 11. Spotted Knapweed Herbage Production on August 3, 1982, 2 Months After Herbicide Application at Harlowton, Ovando, and Stevensville.*

Picloram Rate (kg/ha)	Harlowton 2,4-D amine Rate (kg/ha)		Ovando 2,4-D amine Rate (kg/ha)		Stevensville 2,4-D amine Rate (kg/ha)	
	0.00	2.24	0.00	2.24	0.00	2.24
	Spotted Knapweed Herbage Production (Kg/ha)					
0.28	659.7	193.0	1267.5	1028.9	947.9	564.5
0.25	466.5	260.3	1242.8	1082.5	953.0	526.0
0.22	589.9	313.4	1573.1	984.5	1053.6	937.3
0.21	832.7	396.0	1452.6	971.9	1376.2	616.4
0.14	763.9	224.8	972.7	728.8	1492.4	763.8
0.11	963.6	320.9	1413.9	1139.5	1101.8	839.6
0.07	1022.7	238.9	1563.4	1382.7	1550.5	1179.3
0.00	1607.5	263.8	3991.9	1829.2	2732.0	1070.1
LSD.05	310.9		850.0		780.6	
C.V.%	28.3		31.1		43.3	

*Picloram rates were applied alone and in combination with 2,4-D on June 16, 17, and 18, 1982, respectively.

Table 12. Perennial Grass Herbage Production on August 3, 1982, 2 Months After Herbicide Application to Control Spotted Knapweed at Harlowton, Ovando, and Stevensville.*

Picloram Rate (kg/ha)	Harlowton 2,4-D amine Rate (kg/ha)		Ovando 2,4-D amine Rate (kg/ha)		Stevensville 2,4-D amine Rate (kg/ha)	
	0.00	2.24	0.00	2.24	0.00	2.24
	Perennial Grass Herbage Production (Kg/ha)					
0.28	898.5	836.9	560.5	472.7	296.1	483.8
0.25	727.9	874.0	307.1	596.5	311.3	274.8
0.22	516.4	602.7	682.3	687.7	380.5	268.3
0.21	1159.9	782.0	479.7	829.8	233.8	289.8
0.14	693.1	534.1	440.5	966.6	144.1	652.3
0.11	698.9	648.6	316.5	683.8	392.6	398.6
0.07	704.4	777.5	350.2	651.6	337.2	173.2
0.00	429.5	527.0	360.7	527.5	367.5	165.4
LSD.05	679.9		550.7		380.0	
C.V.%	49.3		51.1		72.3	

*Picloram rates were applied alone and in combination with 2,4-D on June 16, 17, and 18, 1982, respectively.

Table 13. Density of Mature Spotted Knapweed Plants on June 10 and 11, and July 28 and 29, 1983, 12 and 14 Months After Picloram Application at Harlowton and Ovando.*

Picloram Rate (kg/ha)	June 10, 1983				July 28, 1983			
	Harlowton		Ovando		Harlowton		Ovando	
	2,4-D amine Rate (kg/ha)		2,4-D amine Rate (kg/ha)		2,4-D amine Rate (kg/ha)		2,4-D amine Rate (kg/ha)	
	0.00	2.24	0.00	2.24	0.00	2.24	0.00	2.24
	Number of Mature Plants per 0.5 m^2							
0.28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.25	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.11	0.0	0.0	1.6	0.5	0.0	0.0	1.0	0.7
0.07	1.1	0.0	21.0	0.0	0.8	0.0	75.7	0.2
0.0	64.6	0.0	33.5	26.6	84.3	0.0	51.9	39.8
LSD.05	4.86		7.91		1.52		43.43	
C.V.%	61.4		78.9		14.8		212.5	

*Picloram rates were applied alone and with 2,4-D amine on June 16 and 17, 1982, respectively.

Table 14. Density of Immature Spotted Knapweed Plants on June 10 and 11, and July 28 and 29, 1983, 12 and 14 Months After Picloram Application at Harlowton and Ovando.*

Picloram Rate (kg/ha)	June 10, 1983				July 27, 1983			
	Harlowton		Ovando		Harlowton		Ovando	
	2,4-D amine Rate (kg/ha)		2,4-D amine Rate (kg/ha)		2,4-D amine Rate (kg/ha)		2,4-D amine Rate (kg/ha)	
	0.00	2.24	0.00	2.24	0.00	2.24	0.00	2.24
	Number of Immature Plants per 0.5 m^2							
0.28	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.25	1.5	1.3	0.0	0.0	0.0	0.0	0.0	0.0
0.22	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.21	10.1	4.8	0.0	0.0	0.0	0.0	0.0	0.0
0.14	2.3	0.0	0.0	0.0	0.2	0.0	0.2	0.0
0.11	3.6	1.3	0.0	0.0	1.0	0.2	0.5	0.2
0.07	3.6	1.1	1.8	0.0	0.8	0.0	96.8	0.2
0.0	511.6	5.4	676.3	337.8	1454.0	4.8	1020.0	94.3
LSD.05	159.0		251.1		179.8		412.5	
C.V.%	241.2%		204.6		102.0		281.7	

*Picloram rates were applied alone and in combination with 2,4-D on June 16 and 17, 1982, respectively.

Table 15. Spotted Knapweed Herbage Production on July 29 and 30, 1983, 14 Months After Picloram Application at Harlowton and Ovando.*

Picloram Rate (kg/ha)	Harlowton 2,4-D amine Rate (kg/ha) 0.0	Harlowton 2,4-D amine Rate (kg/ha) 2.24	Ovando 2,4-D amine Rate (kg/ha) 0.00	Ovando 2,4-D amine Rate (kg/ha) 2.24
	Spotted Knapweed Herbage Production (Kg/ha)			
0.28	0.0	0.0	0.0	0.0
0.25	0.0	0.0	0.0	0.0
0.22	0.0	0.0	0.0	0.0
0.21	0.0	0.0	0.0	0.0
0.14	0.0	0.0	1.7	0.0
0.11	3.7	0.5	17.9	7.3
0.07	52.2	0.0	210.4	1.0
0.0	2106.6	3.2	1446.6	1535.8
LSD.05	110.2		154.4	
C.V.%	42.1		39.9	

*Picloram rates were applied alone and in combination with 2,4-D amine on June 16 and 17, 1982, respectively.

Table 16. Perennial Grass Production on July 29 and 30, 1983, 14 Months After the Application of Picloram to Control Spotted Knapweed at Harlowton and Ovando.*

Picloram Rate (kg/ha)	Harlowton 2,4-D amine Rate (kg/ha) 0.00	Harlowton 2,4-D amine Rate (kg/ha) 2.24	Ovando 2,4-D amine Rate (kg/ha) 0.00	Ovando 2,4-D amine Rate (kg/ha) 2.24
	Perennial Grass Herbage Production (kg/ha)			
0.28	1700.8	1642.4	1630.8	1808.8
0.25	1747.4	1683.2	1474.0	1899.0
0.22	1287.6	1359.0	1655.4	1758.2
0.21	1979.0	1480.0	2048.0	2052.0
0.14	1466.2	1137.4	1433.8	1579.8
0.11	1472.2	1385.2	1275.0	1776.0
0.07	1437.4	1330.0	1021.2	1676.0
0.00	321.2	930.2	332.0	650.6
LSD.05	871.6		422.8	
C.V.%	32.6		15.2	

*Picloram rates were applied alone and in combination with 2,4-D amine on June 16 and 17, 1982, respectively.

may account for the increase of grass production when picloram treatments were used in combination with 2,4-D amine.

The most effective treatment one year following application was 0.21 kg/ha rate of picloram with or without 2.24 kg/ha of 2,4-D amine at Ovando; and the 0.21 kg/ha rate of picloram alone at Harlowton. There was a greater increase in perennial grass and total forage production with this treatment than with higher or lower rates of picloram, as well as complete control of spotted knapweed. Higher rates of picloram may have injured grasses and caused a reduction in herbage production. Lower rates of picloram did not give complete suppression of spotted knapweed growth, and complete reinfestation of those plots will probably occur in one or two more seasons of growth.

Summary

The trials established by Professor Baker to test the effect of timing of herbicide application continue to show effective suppression of spotted knapweed growth 50 months after treatment at Ovando. Even with heavy grazing use there was a 4 fold increase in desirable forage production at the time of clipping 38 months after treatment at Harlowton. This increase does not include forage which was grazed prior to clipping. Therefore actual grass production at Harlowton was greater than what was collected. The data also suggest that production gains can be lost within one year if even a minimal reinfestation by spotted knapweed occurs. However, with proper management, large increases in perennial grass production for 50 months or more can be obtained from a single application of 0.28 kg/ha of picloram. This longevity of control extends well beyond the predicted period of residual activity of 0.28 kg/ha of picloram (Haymaker et al., 1967). The residual levels of 0.28 kg/ha of picloram 50 months after application should be 0.25 parts per billion (ppb). Fourteen months after the application of 0.07 kg/ha of picloram there should be 0.6 ppb remaining in the soil since 0.07 kg/ha should be 90% dissipated in 6.2

months (Haymaker, 1967). But 14 months after applying the 0.07 kg/ha rate there were clear indications of herbicidal activity on mature spotted knapweed plants, with a 10-fold decrease in the dry weight of treated plants. The number of immature plants present (Table 14) dropped between 12 and 14 months after application indicating either residual activity of picloram, extreme seedling sensitivity to exceedingly low rates of the herbicide, or poor seedling establishment. Perhaps the residual activity of picloram in Montana extends beyond Haymaker's predictions (1967). If so, rates below 0.28 kg/ha may control spotted knapweed plants long enough to exhaust seed reserves in the soil. Combinations of low rates of picloram with 2,4-D amine may offer the most cost-effective control of spotted knapweed. Two,4-D would eliminate mature plants, and the residual activity of picloram would control germinating seedlings until soil seed reserves were exhausted.

Goring and Haymaker (1971) reported that increasing the rate of picloram in the soil will increase the rate of degradation. This is caused by increases in the population of soil microbes that degrade the picloram molecule. Perhaps this accounts in part for the greater persistence of lower rates of picloram than predicted. Lower rates of picloram would not stimulate large increases in microbial populations, and thus not be degraded as rapidly as higher rates.

The picloram residues may have dissipated according to the time frame of Haymaker et al. (1967), and the grass cover that was established on the plots could have hindered spotted knapweed seedling establishment. This grass cover would thus extend the length of time that the plots established by Baker remained free of severe spotted knapweed reinfestation beyond the residual activity of picloram.

Removal of spotted knapweed plants permits a large increase in forage production. Treating spotted knapweed with picloram becomes more attractive when sustained increases in forage production can be obtained with rates of picloram below 0.28 kg/ha. Forage yields were increase for 14 months after treatment with rates of picloram as low as 0.07

kg/ha. The experiment will be maintained for at least three more years to determine if these reduced rates will provide sustained control of spotted knapweed comparable to the 0.28 kg/ha rate.

CHAPTER 3

SEED LONGEVITY OF SPOTTED KNAPWEED IN MONTANA SOILS

Abstract

Spotted knapweed (*Centaurea maculosa* L.) presently infests more than 800,000 ha in Montana. The plant spreads primarily by seed. Experiments were established to measure the longevity of spotted knapweed seed in soil. A seed burial study indicated that the seed of spotted knapweed remained fully viable for 12.5 months. The germination of buried seed was low and no apparent physiological dormancy appears to be associated with the seed. There is a relation between the length of time the seed is buried and decreased seedling vigor.

Field soil reserves of viable spotted knapweed seed declined dramatically in 15 months, however, over 100 viable seeds per 0.5 m^2 still remained in the soil after two seasons without seed production. Cultural practices which may be used on rangeland, including mowing, rolling, harrowing, and burning did not alter the germination of a natural population of spotted knapweed seeds in the soil. A model was constructed to predict the time necessary to exhaust the viable seed reserves in the field based on the witnessed decline of viable seed measured in the field over 15 months. It is estimated that it will take 60 to 75 months to completely exhaust natural seed reserves from soil under Montana conditions.

Introduction

Spotted knapweed's ability to spread rapidly has allowed it to infest over 800,000 ha since its introduction into Montana 60 years ago (Story, 1976). The major cause of spread is the seed production which averages 1000 seeds per plant (Story, 1976). Mature stands can produce 60,000 to 80,000 seeds per m^2. If the seeds of spotted knapweed remain viable in the soil for an extended length of time there would be a logarithmic increase in the seed reserves. However, 97% of the annual seed production is not accounted for when seedling density is measured (personal observation).

No mention of spotted knapweed seed longevity was found in the literature. The length of time seeds remain viable must be known in order for a herbicide program to provide long term control of spotted knapweed.

The objectives of this study were to determine the longevity of spotted knapweed seed under buried soil and natural field conditions, and monitor changes in seedling vigor associated with the length of time that the seed is buried. The effects of various cultural practices on seed germination were also examined.

Methods and Materials

Seed Burial Study

Polyvinyl-chloride (PVC) pipe (7.62 cm diam.) was cut into individual rings 2.54 cm long. Nylon window screen (16 mesh) was cemented to the bottom of each ring. Each ring was filled with soil gathered from the prospective burial site. One hundred spotted knapweed seeds were placed on top of the soil in each PVC ring. Nylon window screen was cemented to the top of each ring.

Fifty rings were buried 1.5 cm deep on 30.5 cm centers at the Post Agronomy Farm, Bozeman, and at the Dale Folkvord farm near Three Forks, Montana on September 22, 1982. The soil and precipitation characteristics of each location are presented (Table 17).

Five seed containers were recovered from each location on 11-11-82, 4-7-83, 5-2-83, 5-16-83, 6-2-83, and 10-10-83. The seeds were separated from the soil by screening and washing. Soil samples were passed through two screens with openings of 10.02 and 3.10

Table 17. Soil and Precipitation Data at the Seed Burial Sites, Bozeman and Three Forks, MT.

	Annual Precipitation	Soil Type
Bozeman	45.7 cm	Agric Pachic Cryboroll
Three Forks	30.5 cm	Tropal-Rock outcrop complex

mm^2 to separate spotted knapweed seeds and extraneous materials. The remaining seed-soil mixture was then placed on a screen (0.55 mm^2 openings) and washed with running water for three minutes to remove more extraneous materials. The seeds were then separated from the remaining organic material by flotation in water. The seeds were skimmed from the water surface, dried, and air cleaned in a South Dakota seed blower (model B, E. L. Erickson Products, Brookings, SD).

The number of seeds that germinated in the field was determined by counting empty seed hulls. Germination tests were performed on the ungerminated seeds by floating them on distilled water for 4 days. Seedling vigor tests were performed on the germinated seedlings by placing them in 16 X 15 X 4 cm germination boxes fitted with moistened blotter paper. The boxes were placed on a 85° slant in a dark germinator at 21°C. Radicle length was measured daily for 5 days. The rate of elongation was calculated by using the following formula outlined in the 1983 Seedling Vigor Testing Handbook of the Official Association of Seed Analysts:

$$\text{Rate of elongation} = \frac{\text{change in radicle length}}{\text{day of observation}}$$

Data was analyzed in a two-way analysis of variance.

Cultural Practice Study

The length of time necessary to exhaust a natural population of spotted knapweed seeds from soil was determined by arresting seed production and monitoring the decline of viable seeds recovered over time. The study was conducted on sites near Harlowton (on a river bottom pasture), and Ovando (on an abandoned hayfield). The soils at both locations were high in gravel and probably Haploboroll soils (see Appendix Table 31 for complete soil information). The climatic data for both locations is given in Appendix Table 33. The 6.1 X 12.2 m plots were arranged in a randomized complete block design with three replications at each location. Four cultural practices, rolling, harrowing, burning, and mowing were used in an attempt to increase seed germination by improving the seed to soil contact. These were compared to a sprayed treatment receiving no cultural practice and totally untreated control.

Seedling densities of mature and immature spotted knapweed plants were taken in two randomly selected 0.09 m^2 locations per plot in late June, 1982, after seedling emergence was complete. Ungerminated spotted knapweed seeds were recovered by taking six 25.6 cm^2 diameter soil cores from each plot. The cores were taken to a depth of 7.6 cm using a tapered tulip bulb planter. Spotted knapweed seeds were recovered from the soil cores by the method described above. All plots except the untreated control were then sprayed with 2.24 kg/ha of 2,4-D amine to prevent seed production for that season. The 2,4-D amine was applied in 142 l/ha of water with a CO_2 pressurized backpack sprayer operated at 40 psi. On September 15, 1982 the mowing treatment was established using a Jari sicklebar mower (Year-a-Round Cab Corp., Mankato, Minn.). The harrowing, burning, and rolling treatments were established on October 30, 1982. Harrowing was done with a fixed tine spike tooth harrow 1.2 m wide pulled at 5 mph. Rolling was done with a lawn roller weighing 136 kg which provided a downward pressure of 17.8 kg per cm^2. Burning was done with a kerosene fired weed burner.

Soil cores were taken as described above on April 20, 1983 to determine the number of viable seeds remaining 10 months after the arrest of seed production. Stand counts were taken at six randomly selected 0.09 m^2 locations per plot on June 15, 1983 to determine seedling emergence. A final series of soil cores was taken on October 10, 1983 to determine the seed reserves in the soil 15 months after seed production was stopped. Data was statistically analyzed in a two-way analysis of variance.

Results and Discussion

Seed Burial Study

The screening and floating procedure for seed recovery was effective since an average of 98% of the buried seeds were recovered (Table 18). Less than 1% of the buried spotted knapweed seeds germinated in the field after 2.5 months of burial (Table 19). Ungerminated seeds in the field after 2.5 month of burial had over 99% viability.

Table 18. Recovery of Spotted Knapweed Seeds in the Seed Burial Study Established on September 21, 1982 at Bozeman and Three Forks, MT.

	Seed Recovery Percentage	
Months of Burial	Bozeman	Three Forks
2.5	100	100
7	99	100
8	100	98
8.5	99	99
9	98	98
12.5	97	95
LSD.05	2	1
C.V.%	1.4	1.1
$\bar{X}$	99	98

The field germination of spotted knapweed seeds was 17% and 12% at Bozeman and Three Forks, respectively, after 7 months of burial (Table 19). Field germination of seed buried 6, 7, 7.5, and 8 months did not vary significantly. Twelve and one half months after burial only 11% of the seeds had germinated at Bozeman; whereas, at Three Forks, 34% of the seed buried had germinated. It was believed that the high percentage of germination at Three Forks was due to field variation. Two of the five sections buried for 12.5 months at Three Forks had over 65% germination while the other three samples germinated 15% to 18%. The rings at Three Forks were buried in a native grassland. The area immediately

Table 19. Percentage of Germination and Viability of Spotted Knapweed Seeds in a Seed Burial Study Established on September 21, 1982 at Bozeman and Three Forks, MT.

Months of Burial	Field Germination (%)		Viability (%) of Ungerminated Seed	
	Bozeman	Three Forks	Bozeman	Three Forks
2.5	1 a[1]	1 a	99 a	99 a
7	17 b	12 c	98 a	100 a
8	12 b	7 b	97 a	100 a
8.5	17 b	7 b	99 a	99 a
9	11 b	4 b	87 b	91 a
12.5	11 b	34 d	91 a	96 a
Unburied	—	—	99 a	99 a

[1] Numbers in a column followed by same letter are not different at the 0.05 level of significance.

above each ring remained bare after burial which created a 7.62 cm^2 open area in the grassland. Settling caused the new surfaces to be slightly depressed. Surface runoff water collected in some of the rings which caused an abnormally high germination of buried seeds at this location. The rings buried at Bozeman were in fallowed soil, so the surface above the rings was not depressed.

While the field germination of seeds buried for 12.5 months was low, the viability of the remaining seeds was high when these seeds were placed in a suitable environment for germination (Table 19). These data indicates that no apparent physiological dormancy is associated with the low rate of field germination. The seeds were not receiving the proper moisture, light, or temperatures required for germination. When the correct stimuli was applied to the seeds, they germinated. The low field germination was not due to immature embryos, internal inhibitors, impermeable seed coats, or other factors which could impose dormancy.

There was no loss of viability in seeds buried for 8.5 months. However, the viability of seeds buried for 9 months fell to 90% or below (Table 19). This trend toward a loss of viability was also seen in rings buried for 12.5 months. Seeds which did not germinate had brown, soft cotyledons, indicating degradation of the seed.

Significant declines in seedling vigor associated with the length of seed burial were seen when the rate of radicle elongation (mm per day) was measured (Figures 1 and 2). Radicles from seeds buried for 12.5 months at Bozeman and Three Forks elongated 21 and 19 mm, respectively, between day one and day two. Unburied seed radicles grew 32 mm at this time. The growth rate of radicles from unburied seeds reached its maximum daily elongation on day three, with 43 mm of new growth. The daily elongation of unburied seeds fell to 25 and 23 mm on days four and five, respectively. The maximum daily elongation for buried seeds was not reached until day four, one day after the peak growth of unburied seeds. Daily radicle elongation of the buried seeds then fell to a significantly lower rate than the unburied seeds on day five (Figures 1 and 2). The greater loss of seedling vigor for seeds buried at Bozeman could be associated with an acceleration of aging caused by the greater precipitation received at this location (Bewley and Black, 1978).

There was very little difference in the rate of seedling elongation between spotted knapweed seed buried for 9 months and the unburied control (Table 20). The rate of elongation for seed buried for 12.5 months was 17% and 25% slower than that of seeds buried for 9 months at Bozeman and Three Forks, respectively. Once again there was an accelerated decline in seedling vigor at Bozeman that may be due to the greater annual precipitation.

Cultural Practice Study

There was an average of 575 viable spotted knapweed seeds per 0.5 m^2 remaining in the soil after seedling emergence was evaluated in late June, 1982 (Table 21). At this time the plots were sprayed with 2,4-D amine to prevent further seed production.

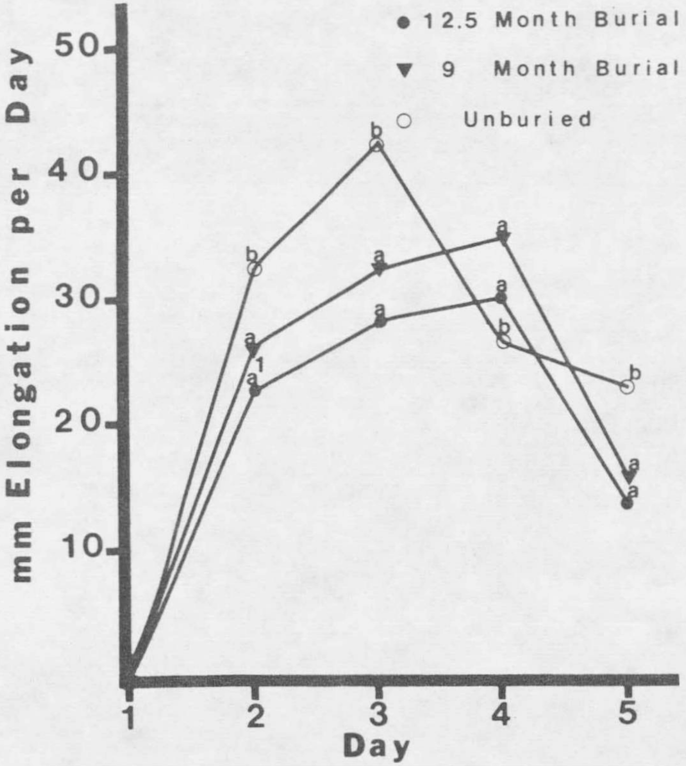

Figure 1. Daily seedling growth of spotted knapweed seeds recovered after 9 and 12.5 months of burial compared to unburied seed at Bozeman.

[1] Points in a column followed by similar letters do not differ significantly at 0.10 level.

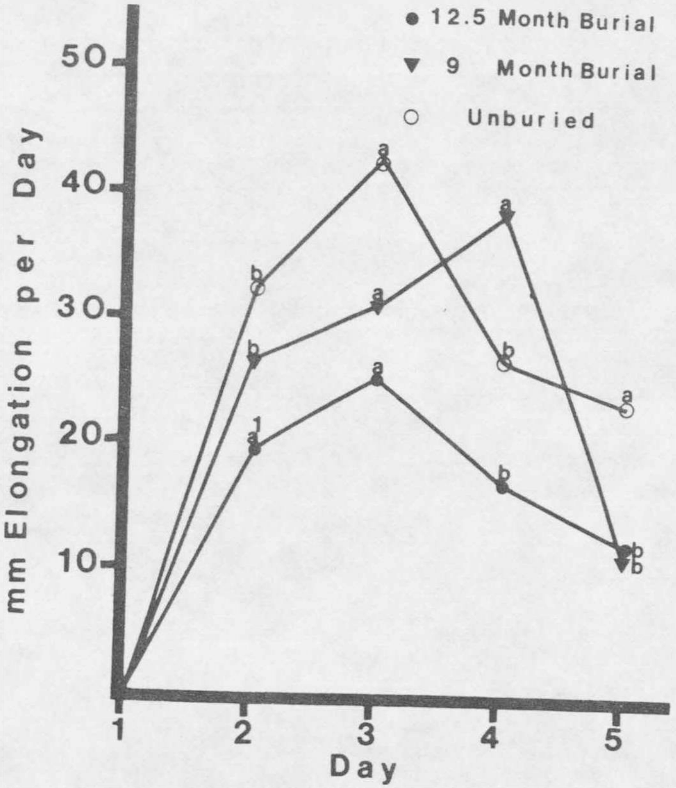

Figure 2. Daily seedling growth of spotted knapweed seeds recovered after 9 and 12.5 months of burial compared to unburied seed at Three Forks.

[1] Points in a column followed by similar letters do not differ significantly at 0.10 level.

Table 20. Rate of Seedling Elongation of Unburied Spotted Knapweed Seed Compared to Seed Buried for 9 and 12.5 Months at Bozeman and Three Forks, MT.

	Rate of Elongation (mm/day)	
Length of Burial	Bozeman	Three Forks
9 months	40.1	43.2
12.5 months	35.6	32.4
Unburied seed	43.0	43.0
LSD .10	3.5	11.7
C.V.	6.0%	20.4%

Table 21. Changes in the Soil Reserve of Spotted Knapweed Seeds 10 and 15 Months After Seed Production was Stopped on 6-20-82, and Various Cultural Practices were Applied to Increase Seed Germination at Harlowton and Ovando, MT.

	Viable Spotted Knapweed Seeds per 0.5 m^2					
	Months After Seed Production was Stopped					
Cultural Practice Treatment	Harlowton			Ovando		
	0	10	15	0	10	15
Harrowing	420a[1]	140b	107b	549a	41b	86b
Rolling	670a	195b	238b	463a	53b	64b
Burning	594a	203b	201b	439a	96b	109b
Mowing	648a	301ab	246b	447a	22b	164b
Sprayed check	248a	92b	115b	502a	96b	53b
Control	523a	564a	1214a	603a	607a	635a
C.V.	30.3%	16.3%	15.9%	16.5%	14.5%	13.8%

[1] Numbers followed by the same letter in the same column do not differ significantly at the 0.05 level.

The reservoir of viable seeds in the plots treated with 2,4-D amine on June 1982 had declined 72% and 87%, respectively, by 4-20-83 (10 months) at Harlowton and Ovando. There was a slight increase (0.7% to 8%) in the viable seed reserves between 6-20-82 and 4-20-83 (0 to 10 months) in plots where seed production was permitted in the fall of 1982 (Table 21 and Figures 3, 4, 5, and 6). Seed reserves in control plots increased 115 and 5% at Harlowton and Ovando, respectively, following fall seed production in 1983. The small (5%) increase at Ovando was influenced by an early fall snow storm which caused seed germination before soil cores could be taken. The sharp decline in soil reserves of viable seed

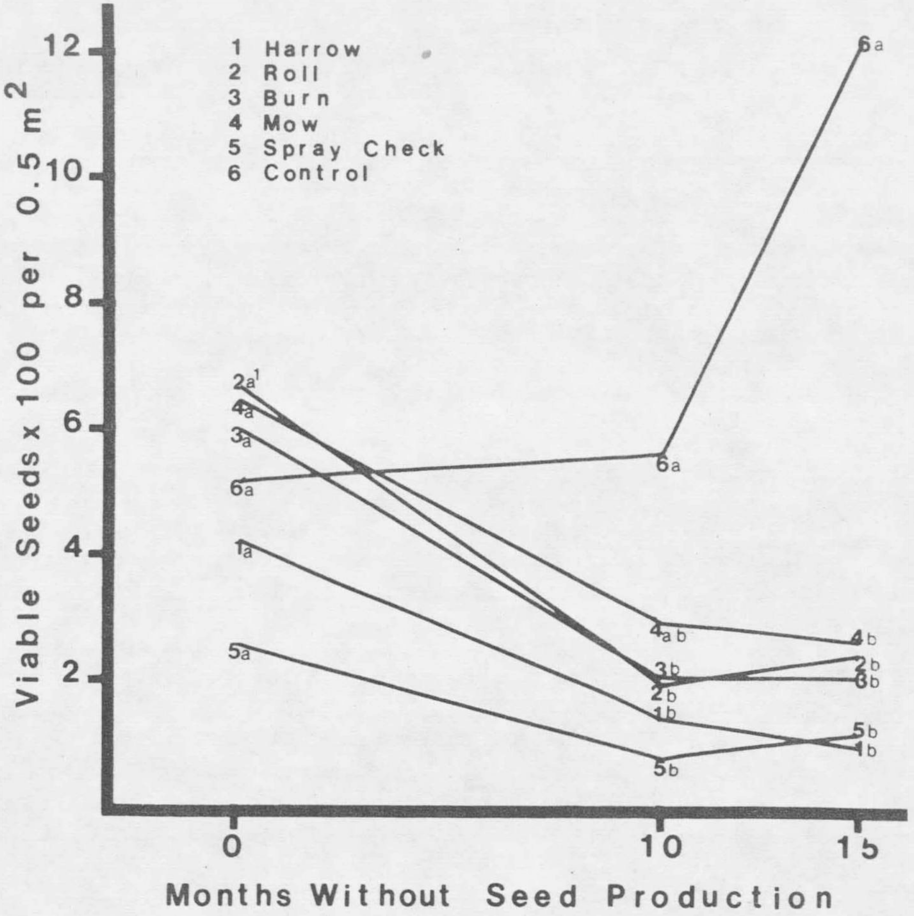

Figure 3. Changes in the soil reserve of spotted knapweed seeds 10 and 15 months after seed production was stopped on 6-20-82, and various cultural practices were applied to increase seed germination at Harlowton.

[1] Points in a column followed by similar letters differ significantly at 0.05 level from other points.

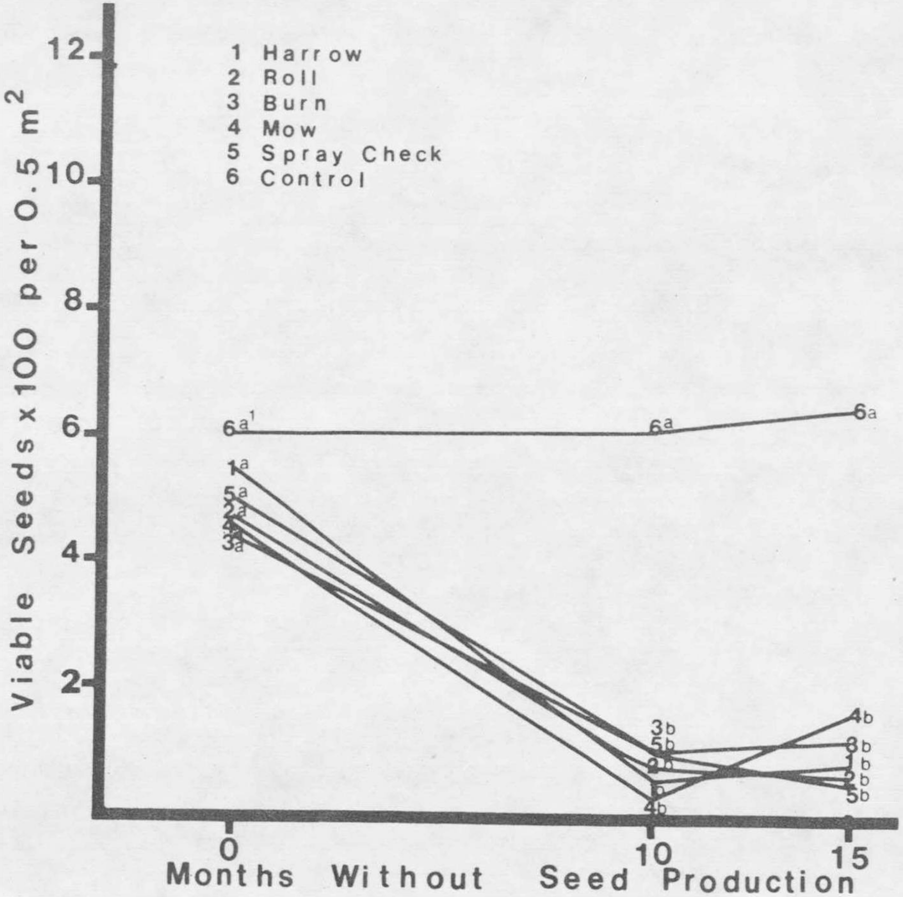

Figure 4. Changes in the soil reserve of spotted knapweed seeds 10 and 15 months after seed production was stopped on 6-20-82, and various cultural practices were applied to increase seed germination at Ovando.

[1] Points in a column followed by similar letters do not differ significantly at 0.05 level.

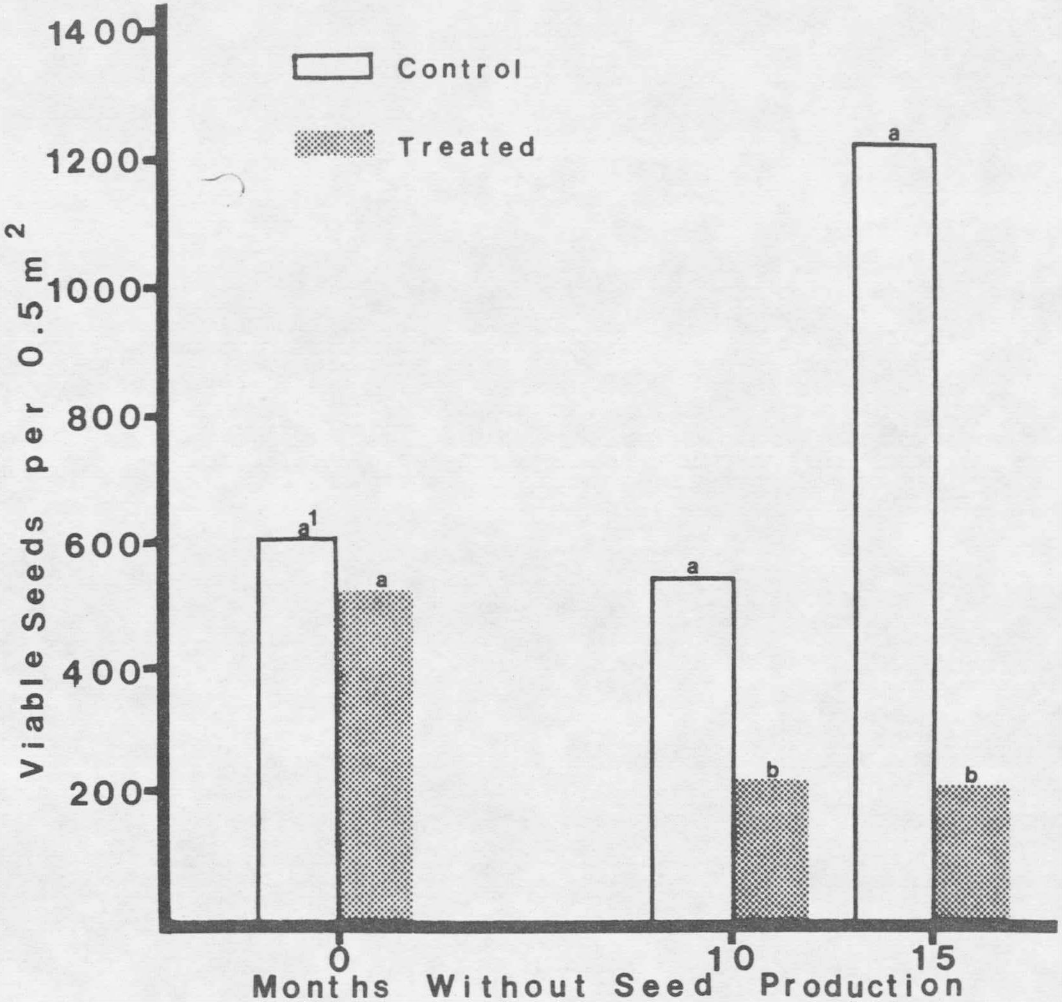

Figure 5. Changes in the soil reserve of spotted knapweed seed 0, 10 and 15 months after seed production was stopped at Harlowton.

[1] Bars with similar letters at 0, 10 and 15 months, respectively, do not differ at 0.05 level of significance.

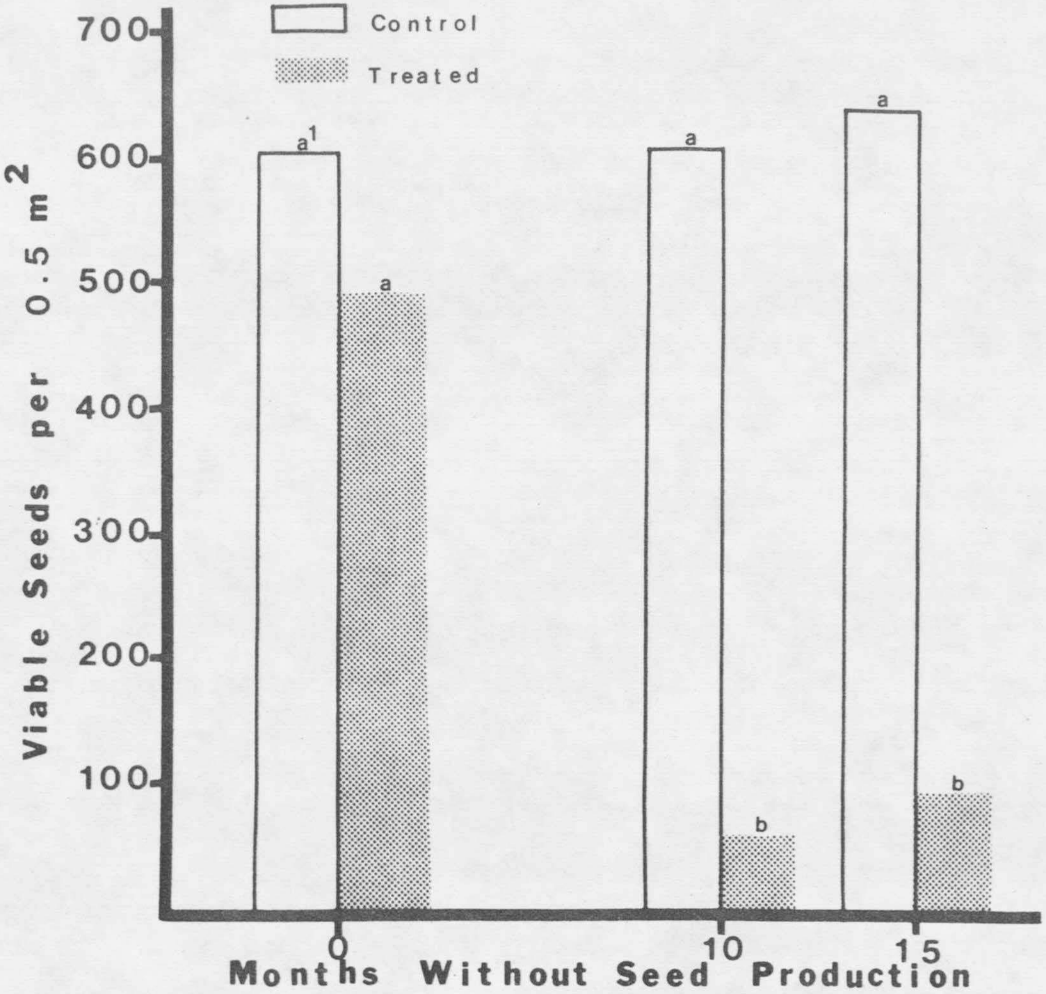

Figure 6. Changes in the soil reserve of spotted knapweed seed 0, 10 and 15 months after seed production was stopped at Ovando.

[1] Bars with similar letters at 0, 10 and 15 months, respectively, do not differ at 0.05 level of significance.

over a relatively short period of time (10 months) indicates the short longevity of seed viability under natural field conditions.

The various cultural practices did not influence the stand density of seedling or mature spotted knapweed plants one year after seed production was stopped (Table 22). In addition, the combination of the various cultural practices and spraying with 2,4-D amine had no effect on seedling density compared to spraying with 2,4-D alone. The practices appeared to have no effect on the seed germination since no increase in seedling emergence was observed. However, all cultural practices and 2,4-D sprayings did significantly reduce seedling and mature plant densities compared to the untreated control (Table 22).

Table 22. Seedling and Mature Plant Density of Spotted Knapweed on June 13, 1983 One Year After Treatment With 2,4-D Amine at Harlowton and Ovando, MT.

	Mature Plants/0.5 m²		Seedlings/0.5 m²	
Treatment	Harlowton	Ovando	Harlowton	Ovando
Harrowing + 2,4-D	0.0 a[1]	7.3 a	2.0 a	19.7 a
Rolling + 2,4-D	0.0 a	7.7 a	1.7 a	14.7 a
Burning + 2,4-D	0.0 a	6.7 a	12.8 a	22.8 a
Mowing + 2,4-D	0.0 a	7.9 a	3.6 a	24.6 a
2,4-D check	0.0 a	0.0 a	2.0 a	14.2 a
Control	31.2 b	29.7 b	88.9 b	903.8 b

[1] Numbers in columns followed by same letter do not differ at the 0.05 level of significance.

Soil samples were taken on 10-10-83 (after 15 months) to determine the soil reserves of viable spotted knapweed seed. Although seed production was prevented with a second treatment of 2,4-D amine in June of 1983 (Table 21), the seed reserves did not change significantly from April to October 1983. On plots where seed production was allowed there was an increase in the seed reserves from April to October 1983.

A majority of the April seed reserves in treated plots which germinated between April and June, 1983, did not become established plants. Only 10 and 39% of the seed reserves present on a 4-20-83 at Harlowton and Ovando germinated and produced seedlings by

6-13-83 (Figures 7 and 8). However, the density of seedlings on untreated plots on 6-13-83 accounted for 85 and 149% (Harlowton and Ovando, respectively) of the seed reserves on 4-20-83 (Figures 7 and 8). Although the 149% figure at Ovando indicates there were more June seedlings than April seeds, the seedling count was magnified by a large seed germination in the fall of 1982. There are two possible explanations for this; first, the seeds did germinate, but did not become established because of the increased grass competition which resulted when the allelopathic influence of spotted knapweed was removed (Watson and Renney, 1974), or the seeds did not germinate because of poor environmental conditions for germination.

Summary

Spotted knapweed seeds remained viable after 12.5 months of burial. Unburied spotted knapweed seeds germinated rapidly and exhibit the greatest increase in radicle elongation during the first 3 days following germination. Seed which was buried for 9 months germinated slower and did not exhibit the rapid initial growth of unburied seed in the lab test. The maximum rate of radicle elongation for seed buried for 9 months was not reached until later than unburied seed. Once the maximum rate of elongation (which is less than unburied seed) was reached, it dropped to a level less than that of unburied seed.

The rate of seedling elongation of seeds buried for 12.5 months follows the same pattern of radicle elongation established by seeds buried for 9 months, however, the rate of elongation was 25% less than that of unburied seeds (Table 21). Seeds buried at Bozeman had a larger drop in vigor than seeds buried at Three Forks. These differences were probably due (in part) to the differences in precipitation received at the two locations.

The decreases in the vigor of spotted knapweed seed buried for 12.5 months were significant. These changes could mark the beginning of dramatic alterations in the quality

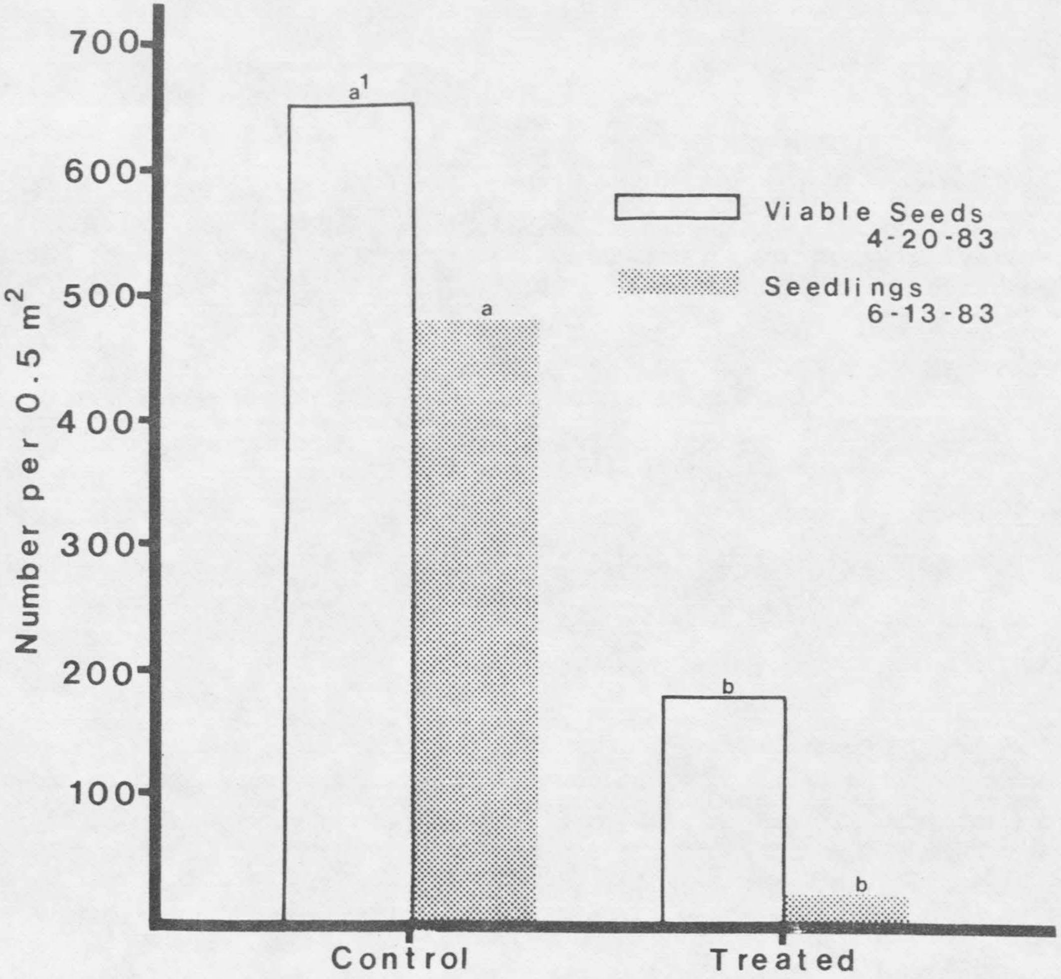

Figure 7. Spotted knapweed seedling density on June 13, 1983, from soil seed reserves on April 20, 1983, as affected by 2,4-D treatment on June 20, 1982 at Harlowton.

[1] Seed and seedling densities followed by similar letters, respectively, do not differ at 0.05 level of significance.

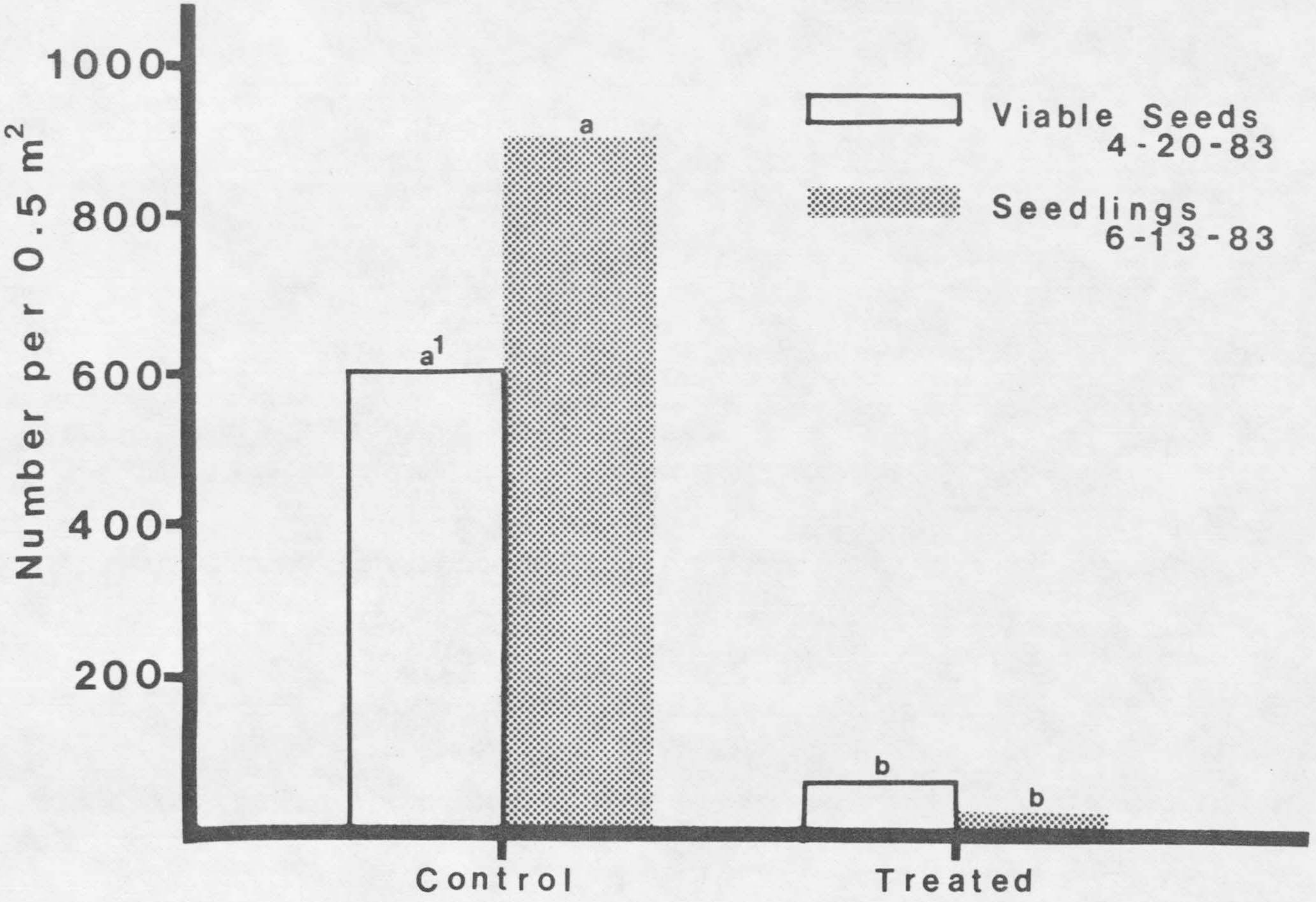

Figure 8. Spotted knapweed seedling density on June 13, 1983, from soil seed reserves on April 20, 1983, as affected by 2,4-D treatment on June 20, 1982 at Ovando.

[1] Seed and seedling densities followed by similar letters, respectively, do not differ at 0.05 level of significance.

of the buried seed. There was a large decrease in the number of viable seeds recovered from soil cores taken in the cultural practice study after an overwintering period. During this time the seeds imbibed water, but temperatures were too low for germination and seed degradation occurred. The seeds in the burial study showed slight changes in vigor and viability during an overwintering period. Perhaps after two overwintering periods these changes will become more dramatic. The sharp decline in the seed reserves from the treated plots of the cultural practice study could be caused by the loss of older (2 or more years) seeds that had started the degradation process in previous winters. The seeds that remained in the soil on 10-10-83 had only gone through one overwintering period and had therefore just begun the degradation process. This placed the viable seeds in a position similar to those in the burial study after 12.5 months. The seed reserves decline from losses of older seeds probably occurred in the control plots, but were not measured because of a replenishing by annual seed production.

The exact longevity of spotted knapweed seed in the soil remains to be fully discovered. Even though sharp declines were measured in the soil seed reserves after 15 months, a sufficient seed population remained to insure reinfestation after two years without seed production. The soil reserves of viable spotted knapweed seed declined 72% and 81% in 15 months at Harlowton and Ovando, respectively (Table 23). This rate of decline of the seed reserves might be useful as a "degradation constant" for projecting the decline of spotted knapweed seeds from the soil over time (Table 24 and Figure 9).

Table 23. The Degradation of Spotted Knapweed Seed Reserves in a Field Situation Based on Declines Witnessed Over 15 Months at Harlowton and Ovando, MT.

	Soil Seed Reserves		% Decline in Seed Reserves
Location	6-20-82	10-10-83	in 15 Months
Harlowton	647	181	72
Ovando	501	96	81

Table 24. The Degradation of Spotted Knapweed Seed Reserves in the Soil at Two Locations in Montana Based Upon Observed Declines Over a 15 Month Period.

Viable Seeds per .5 m^2		
Harlowton	Ovando	Months to Decline
647	501	
181	96	15
51	18	30
14	4	45
4	0.67	60
1	0.12	75

The more rapid degradation of viable seed reserves at Ovando than at Harlowton may be due to differences in annual precipitation at the two locations. Ovando receives an average of 45.7 cm per year compared to 35.6 cm at Harlowton. This relationship between annual precipitation, and vigor losses was also observed in the burial study. Based on a continued steady rate of decline, where the degradation constant is defined as the rate of decline of viable seeds per 0.5 m^2 in 15 months, it would take approximately 75 months without seed introduction to reduce soil seed reserves at Harlowton to a level of 1 seed per 0.5 m^2, and 60 months to decrease reserves to similar levels at Ovando. During this time seed production could be stopped with an annual application of 2.24 kg/ha of 2,4-D amine applied in the mid-June, or an application of 0.28 kg/ha of picloram applied every 36 months. These degradation predictions may be influenced by the grass cover that is established when the allelopathic influence of spotted knapweed (Fletcher and Renney, 1963) is removed. Although viable seeds are present in the soil reserves, the declines in seedling vigor, as seen in the burial study, may hinder seedling establishment amidst the increased grass competition. This would shorten the length of time necessary to exhaust the soil reserves of spotted knapweed seeds that are capable of producing mature plants. These experiments will be monitored for three more years in an attempt to verify the accuracy of these predictions.

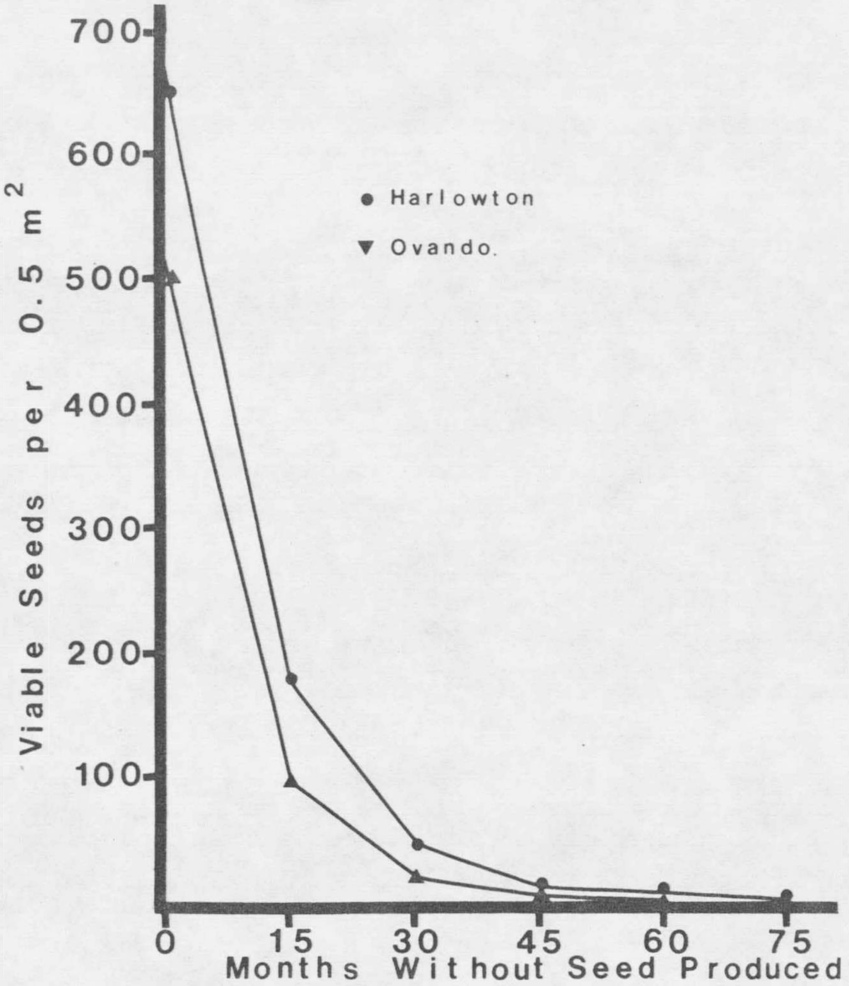

Figure 9. The projected decline of spotted knapweed seed reserves in the soil at 2 locations in Montana based upon observed declines over a 15 month period.

CHAPTER 4

A SIMPLE TECHNIQUE FOR PREDICTING WEED MIGRATION

Abstract

A simple technique for predicting weed migrations is described. Six edaphic and climatic characteristics (soil type, elevation, annual precipitation, potential evapotranspiration, length of frost-free season, and mean maximum July temperature) were measured for 116 locations in Montana which contained established infestations of spotted knapweed (*Centaurea maculosa* L.) using basic land resource information maps of Montana. Areas of the state that have a high probability of supporting the growth of the plant as defined by the edaphic and climatic characteristics were highlighted with acetate blockout film. It is estimated that 50% of Montana is threatened by this rangeland invader. Because the seed is readily disseminated along all transportation corridors, weed district supervisors should watch these areas and when small problem areas are located measures should be initiated without delay. This technique shows promise for delineating suitable habitats of other invader species as well as spotted knapweed.

Introduction

Spotted knapweed (*Centaurea maculosa* L.), a native of Eurasia, has become especially troublesome in the Rocky Mountain region of the northern U.S. and Canada (Maddox, 1979). The plant was first reported in Montana in the 1900s (Forcella and Harvey, 1981) and presently infests almost 800,000 ha. The present infestation is located primarily west of the Continental Divide, however several major infestations have been reported east of the Divide. This indicates the plant may pose a threat to the vast grazing lands of eastern Montana as well as those in the adjoining states and provinces. The ability to predict the migration of invader species such as spotted knapweed would allow for the use of preventive measures which are considerably cheaper than large scale control treatments of established weed infestations.

Few attempts have been made to predict the ability of a plant species to grow in a region based on the edaphic or climatic characteristics of that region. Holdridge (1947) attempted to determine the plant complexes of the world using variables such as temperature, precipitation, evaporation, and elevation. The plant complexes were divided into categories including moist tundra, desert bush, prairie, or moist forest. Duke (1976) reversed this theory, and used perennial weeds as indicators of the annual climatic parameters of a given area. He felt that by knowing the climatic requirements of a weed suitable ecological niches for the plant could be identified in areas where it is not currently found. His predictions were based on the soil pH range of the plant, annual precipitation, annual temperature, the number of warm, wet months, and a broad category called "life zones." The life zone category was subdivided into broadly defined areas such as Subtropical, Boreal, and Steppe.

Reus and Bachthaler (1979) presented data on a correlation index derived from weed surveys and meteorological factors associated with the presence of the various species. Lindsay (1953) conducted a frequency survey of weed infestations in Wisconsin and compared the frequency of occurrence with July evaporation. He concluded by saying that the range of a weed could be predicted by climatic data. Confirmations were made by comparing regions where specific weeds were present in Wisconsin with weeds in areas of Ontario with similar climatic conditions. Harris and Cranston (1979) estimated the number of acres susceptible to invasion by diffuse (*Centaurea diffusa* L.) and spotted knapweed

(*C. maculosa* L.) in Canada. They based their predictions entirely upon the soil types in Canada which are similar to soils which support the knapweeds at their center of origin.

Since chemical control is often not economically feasible for established infestations, the early detection and treatment of spotted knapweed and other invader species is critical. This study was conducted to determine the areas of Montana that may be threatened by invasion of spotted knapweed.

Materials and Methods

One hundred sixteen infestations of spotted knapweed were selected for the study (Figure 10). Each infestation covered at least 0.4 ha and was well established on grazing land. Small infestations on disturbed sites were not included in the study. The infestations occurred in 13 of the 16 counties (Figure 11) selected throughout the state on the basis of the quality of the county weed personnel.

Characteristics of the Infestation Sites

The adaptability of a plant is governed by a series of edaphic and climatic characteristics which include soil type, elevation, annual precipitation, potential evapotranspiration, length of frost-free season, and the mean maximum July temperature. These characteristics have been mapped for individual states on basic land resource maps. Single edaphic and climatic characteristics for each of the test infestations were plotted on individual maps.

The frequency of occurrence of the test infestations in each zone of a given characteristic was measured (Tables 25-29). If an infestation occurred on the boundary between two zones, that infestation was counted as being in both zones. Thus the total number of infestations on the annual precipitation, elevation, length of frost-free season, potential evaporation, and mean maximum July temperature maps contain a total of more than 116 infestations (Tables 25-29). The soil type map was dealt with in a different manner. The large