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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APPROVAL

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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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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).