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Distribution, Biology, and Management of Diffuse Knapweed (*Centaurea diffusa*) and Spotted Knapweed (*Centaurea maculosa*)[1]

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Abstract: Diffuse knapweed, a biennial or short-lived perennial, and spotted knapweed, a perennial, are taprooted Eurasian weeds invading rangeland in the western United States and Canada. Knapweed (*Centaurea* spp.) invasion is associated with reductions in biodiversity, wildlife, and livestock forage, and increased erosion. Spotted knapweed grows to about 1 m and usually has purple flowers, whereas diffuse knapweed is slightly shorter, usually with white flowers. Persistent flower bracts on diffuse knapweed bear a rigid terminal spine about 8 mm long with four or five pairs of shorter lateral spines. Bracts on spotted knapweed have dark spotted tips. Knapweed management involves a combination of containing infestations and control efforts. Hand pulling in areas with small infestations can be effective for controlling spotted and diffuse knapweeds. Picloram applied at 0.28 kg ha^{-1} provides control for about 3 yr. Effective long-term control of knapweeds requires periodic applications of picloram, which are only cost-effective on highly productive range sites with a residual grass understory. About 12 insect species have been released for knapweed biocontrol. Seed production has been reduced by 46% by insects feeding in the flower heads. Although insects have not reduced spotted knapweed densities, they may stress the weed and shift the competitive balance to associated species. Sheep grazing reduces the density of very young seedlings and may limit seedling recruitment into the population. In areas without a residual understory of desired plant species, revegetation of knapweed-infested rangeland is required. Components of any integrated weed management program are sustained effort, constant evaluation, and the adoption of improved strategies.
Nomenclature: Picloram, 4-amino-3,5,6-trichloro-2-pyridinecarboxylic acid; diffuse knapweed, *Centaurea diffusa* Lam. #[3] CENDI; spotted knapweed, *Centaurea maculosa* Lam. # CENMA.
Additional index words: Noxious rangeland weeds, integrated weed management, sustainable weed management, CENDI, CENMA.

INTRODUCTION

Diffuse and spotted knapweeds are native to grassland steppes of southeastern Europe and Asia Minor. Diffuse knapweed grows in the eastern Mediterranean area, in western Asia, and from the southern part of former U.S.S.R. to western Germany (Rees et al. 1996). Diffuse knapweed grows best on fertile, well-watered Cryoborolls, mesic Argiudolls, and mesic Hapludolls in open and uncultivated sites with a summer drought, but can tolerate a wide range of precipitation and temperature (Harris and Cranston 1979). Watson and Renny (1974) reported that diffuse knapweed has been observed growing at elevations ranging from 150 to over 900 m. More recently, diffuse knapweed has been found thriving at elevations up to 2,600 m.

The native range of spotted knapweed is central Europe and east to central Russia, Caucasia, and western Siberia (Rees et al. 1996). In Europe, spotted knapweed is most aggressive in the forest steppe on Mollisols and mesic Aridisols, but can form dense stands in more moist areas on well-drained soils including gravel, and in drier sites where summer precipitation is supplemented by runoff. Spotted knapweed does not compete with vigorously growing grass in moist areas, nor with diffuse knapweed in steppic grassland. It occurs on the moist end of the range of diffuse knapweed

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[3] Letters following this symbol are a WSSA-approved computer code from *Composite List of Weeds,* Revised 1989. Available from WSSA, 810 East 10th Street, Lawrence, KS 66044-8897.

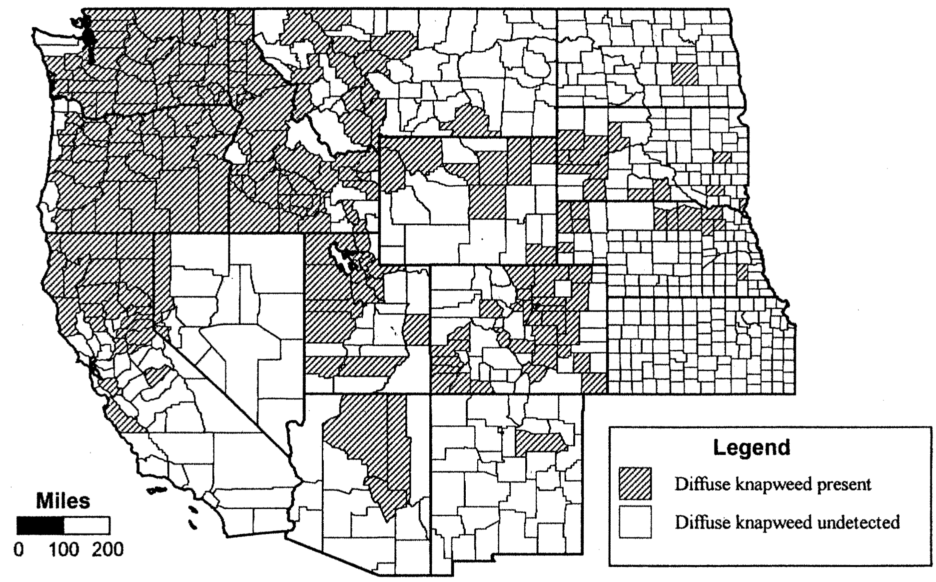

Figure 1. The current distribution of diffuse knapweed determined from herbarium records and interviews with weed authorities from 15 states in the western United States.

(Harris and Cranston 1979). Lacey et al. (1995) reported that spotted knapweed has been observed at elevations ranging from 578 to over 3,040 m and in precipitation zones ranging from 20 to 200 cm, annually.

DISTRIBUTION OF DIFFUSE AND SPOTTED KNAPWEED

Diffuse and spotted knapweed were introduced to North America from Eurasia as contaminants in alfalfa (*Medicago sativa* L.) (Muller et al. 1988; Roché et al. 1986). Spotted knapweed was also apparently introduced through discarded soil used as ship ballast (Roché et al. 1986). Diffuse knapweed was first recorded in North America in Washington in 1907 (Howell 1959), and spotted knapweed was first recorded in Victoria, British Columbia, in 1893 (Groh 1944). Both knapweeds spread further in domestic alfalfa seeds and hay before they were recognized as serious problems (Roché et al. 1986).

We have documented the geographic spread of diffuse and spotted knapweeds in the western United States up to 1980 using herbarium records compiled by Forcella and Harvey (1980), and current distribution through interviews with weed authorities in the region (Figure 1). Diffuse knapweed was first recorded from an alfalfa field at Bingen, Klickitat County, Washington (Roché and Talbott 1986). By 1980, it had spread to 26 counties in the Pacific Northwest. Between 1980 and the present, diffuse knapweed had extended its range to include 204 counties in 14 western states. In the United States, spotted knapweed was limited to the San Juan Islands, WA, until 1920. This weed had spread to 20 counties in the Pacific Northwest by 1960 and to 48 counties by 1980. Between 1980 and the present, the known range of spotted knapweed rapidly increased to include 326 counties in the western United States, including every county in Washington, Idaho, Montana, and Wyoming (Figure 2).

IDENTIFICATION

Diffuse and spotted knapweeds are deeply taprooted rosette-forming plants of the Asteraceae family. Basal rosette leaves are born on short pedicels and grow up to 20 cm long and 5 cm wide. Rosettes are deeply divided (once or twice) into lobes on both sides of the center vein (Figures 3a and 3b). Lobes are oblong with the broadest part above the middle. Flowering stems are erect 2 to 12 cm tall. Diffuse knapweed has many spreading branches, giving it a ball-shaped, tumbleweed appearance and mobility, whereas spotted knapweed stems branch on the upper half of the stem and are not ball shaped. Stem leaves for both species are alternate, sessile, have few lobes, or are linear and entire, and are reduced toward the stem apex. The uppermost leaves are small and simple. Flower heads are ovate to oblong, 6 mm wide and 12 mm long, and are solitary or born in clusters of two or three at the branch ends. Involucre bracts are foliaceous, ovate, and yellow-green to brown below. Margins have a soft, spinelike fringe with the center spine longer and spreading on diffuse knapweed (Figure 3c), whereas the center spine is shorter than the lateral ones on spotted knapweed. Spotted knapweed

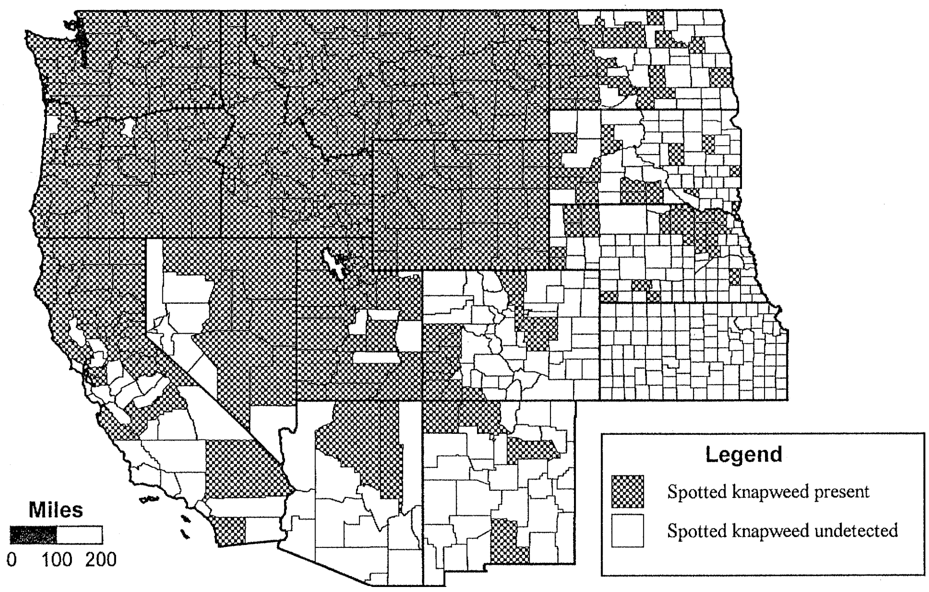

Figure 2. The current distribution of spotted knapweed determined from herbarium records and interviews with weed authorities from 15 states in the western United States.

also has a black margin at the bract tips and obvious longitudinal veins (Figure 3d), whereas bract margins of diffuse knapweed are buff or brown. Most flowers of diffuse knapweed are white, but occasionally, they are rose to lavender, with about 10 to 15 flowers on each flower head (Strang et al. 1979). Spotted knapweed flowers are purple to pink, rarely white, with 25 to 35 flowers/head. Diffuse knapweed flowers from late June to September. Flower heads fall from the plant when seeds are mature. Seeds are 2 to 3 mm long and dark brown. The pappus is generally absent or slightly less than 1 mm long. Spotted knapweed flowers bloom from June to October. The flower heads usually remain on the plant. Seeds are 3 mm long, oval, brown to black, with pale longitudinal lines. Seeds bear a pappus of simple bristles that are 1 to 2 mm long and persistent.

BIOLOGY AND ECOLOGY

Impacts. Diffuse and spotted knapweeds reduce livestock forage. Watson and Renny (1974) found decreased bluebunch wheatgrass [*Pseudoroegneria spicata* (Parsh) Love] yield was correlated with increased production of spotted knapweed. Bluebunch wheatgrass-rough fescue (*Festuca scabrella* Torr.) production was reduced by 88% by knapweed invasion (Watson and Renny 1974).

Knapweeds also have a negative impact on wildlife. Elk (*Cervus canadensis*) use, as estimated by pellet groups/hectare, was reduced by 98% on spotted knapweed-dominated range compared to bunchgrass-dominated sites (Hakim 1979). Spoon et al. (1983) predicted a loss of 220 elk annually in Montana because of spotted knapweed infestations on winter range.

Knapweed infestation on bunchgrass rangeland is also detrimental to water and soil resources. Lacey et al. (1989) determined that surface water runoff and stream sediment yield were 56 and 192% higher, respectively, for spotted knapweed-dominated sites compared to bunchgrass-dominated sites. Bareground and water infiltration rates were greater on sites with unclipped bunchgrass than on those with spotted knapweed (Lacey et al. 1989).

Nutritive Content. Diffuse and spotted knapweed rosettes and young flower shoots have some nutritive value (Fletcher 1961). Nutrient analysis of spotted knapweed collected before flowering showed neutral detergent fiber at 24.2 to 53.0% (dry wt), ether extract 3.1 to 9.0%, crude protein 6.2 to 18.2%, total nonstructural carbohydrates 11.0 to 27.5%, ash 4.9 to 9.3%, in vitro dry matter digestibility 53.2 to 61.8%, and gross energy 4,088 to 4,539 cal/g (Kelsey and Mihalovich 1987). Kelsey and Mihalovich (1987) observed crude protein and nonstructural carbohydrates were most concentrated during the spring, becoming more fibrous with lower protein and carbohydrate levels as stems matured during the summer. Diffuse and spotted knapweeds are grazed by deer (*Odocoileus* spp.) and sheep (*Ovis aries*) (Olson et al. 1997). These knapweeds also provide nectar and pollen for domestic bees (*Apis mellifera*) (Watson and Renny 1974).

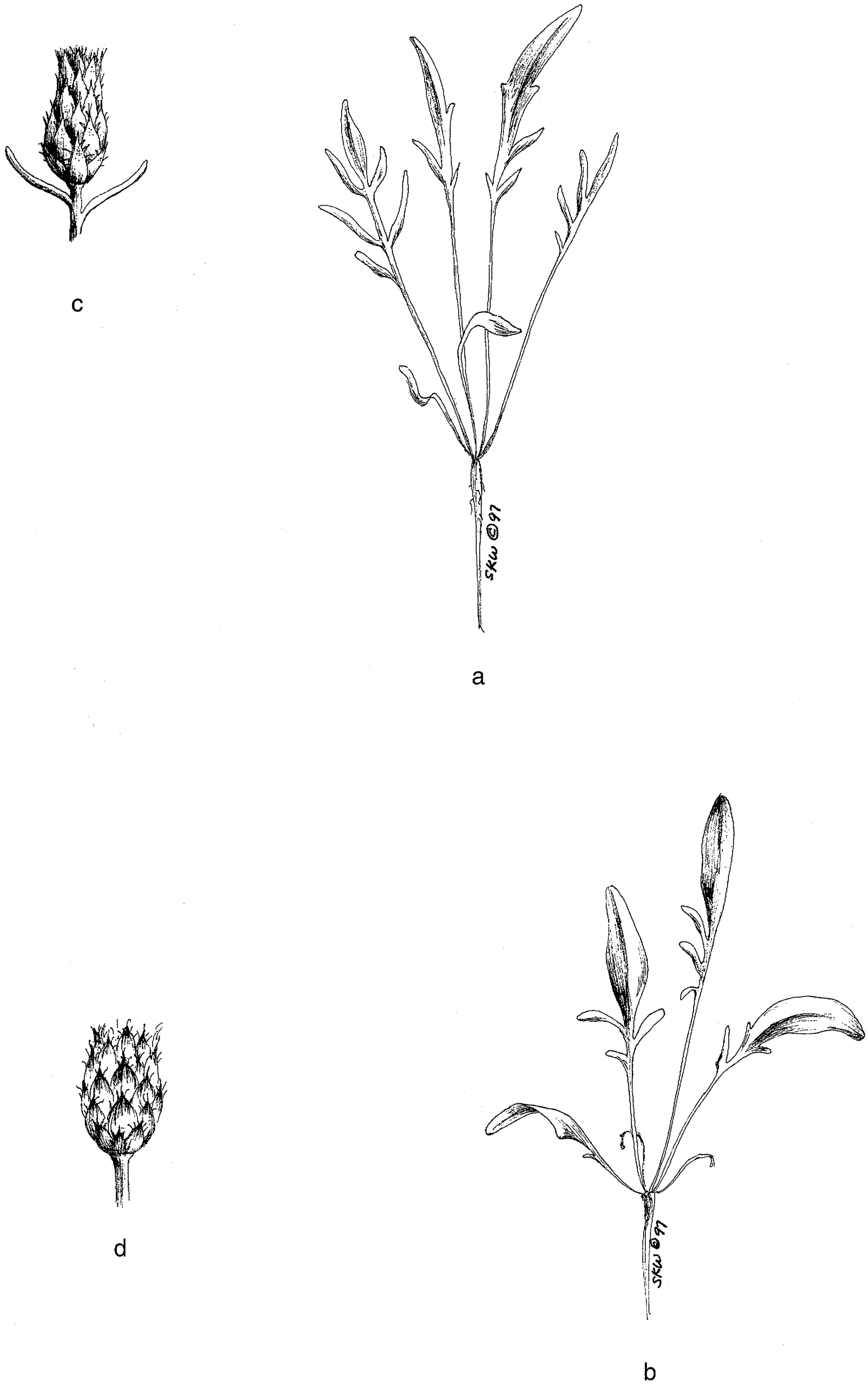

Figure 3. Diffuse and spotted knapweed rosettes and flower heads. *a*-diffuse knapweed rosette, *b*-spotted knapweed rosette, *c*-diffuse knapweed flower head showing characteristic involucre bracts, *d*-spotted knapweed flower head showing characteristic involucre bracts.

Phenology. Diffuse knapweed is a semelparous perennial (Nolan and Upadhyaya 1988). It may complete its life cycle in a single year, or live for several years as a rosette before flowering. It can also continue to grow after producing seeds to flower again the following year (Roché and Roché 1993). Spotted knapweed is a perennial that lives up to 9 yr and is capable of producing seeds in each year (Boggs and Story 1987). Seed production of diffuse knapweed ranges from 11,200 to 48,100 seeds/m^2, and for spotted knapweed 5,000 to 40,000 seeds/m^2 (Shirman 1981). Site conditions and precipitation during the growing season have the greatest effect on the number of seeds produced per year. More seeds are produced during wet years (Shirman 1981).

Seeds germinate in the fall and early spring when moisture and temperature are suitable (Watson and Renny 1974). Fall and early spring germinating seedlings are capable of maturing into seed-producing adults in 1 yr (Shirman 1981). Seedlings develop into rosettes, and maximal root growth occurs at this stage (Watson and Renny 1974). If rosettes do not bolt, they die back to the root crown, which serves as the perennating part of the plant over winter. Root crowns form rosettes in the early spring and bolt in early May. Diffuse knapweed produces one stem, rarely two, whereas spotted knapweed produces one to six stems (Watson and Renny 1974). Flowering buds form in early June, and flowering occurs from July through September. Mature seeds form by mid-August. Most spotted knapweed seeds are shed upon maturity with few overwintering in the seedheads, whereas diffuse knapweed delays seed shed.

Spread. Seed (achene) dispersal of diffuse knapweed is mainly by wind. Mature plants break off at ground level and tumble in the wind or become attached to the undercarriage of vehicles and equipment (Watson and Renny 1974). Seeds are released through a small opening at the tip of the flower head when the persistent dry flowers are dislodged, usually by the action of tumbling (Roché et al. 1986). Seeds are also carried in mud and by rodents. In contrast, spotted knapweed plants do not break off at ground level, and populations are largely extended through peripheral enlargement of existing stands (Watson and Renny 1974). Bracts of the flower heads open when dehydrated, 2 to 3 wk after maturity, and movement of the stem by wind or passing animals can flick the loosely held achenes up to 1 m from the parent plant (Watson and Renny 1974). Long-distance transport occurs when achenes become attached to passing animals, or by rodents and birds. Spotted knapweed flower heads also become attached to the undercarriages of vehicles, are transported long distances in mud, and commonly become attached to or drop into shoes. Seeds of both diffuse and spotted knapweeds spread through rivers and along watercourses, and are transported in crop seed and hay.

Germination. Diffuse and spotted knapweed seeds germinate over a wide range of environmental conditions. Watson and Renny (1974) reported germination occurs for both species at temperatures ranging from 7 to 34 C, with optimum germination at about 24 and 19 C for diffuse and spotted knapweed, respectively. Seeds germinate in the light and dark; however, maximum germination occurs in an alternating light and dark environment (Watson and Renny 1974). They also found that 20 to 40% of diffuse and spotted knapweed seeds, respectively, germinated when removed from flower heads at maturity, which improved to 68 and 80% 25 d after removal. Optimum emergence occurs at the soil surface with little emergence below 5-cm depth (Watson and Renny 1974). Seedling mortality averages about 12%, but can be as high as 55% (Watson and Renny 1974).

Seeds of diffuse and spotted knapweeds have three types of germination behavior: nondormant seeds, which germinate in the dark; light-sensitive dormant seeds, which germinate after exposure to red light; and light-insensitive dormant seeds, which do not respond to exposure to red light (Nolan and Upadhyaya 1988). Individual plants can produce seeds of all three germination types.

Davis et al. (1993) determined that although spotted knapweed seeds decreased by 95% over a 7-yr period, approximately 40,000 viable seeds/ha remained. Wallander et al. (1995) reported that up to 22% of spotted knapweed seeds can remain viable after passing through the digestive tracts of sheep and mule deer (*Odocoileus hemionus* spp. *hemionus*). In that study, viability of seeds passed through the digestive tracts decreased as time after ingestion increased.

Diffuse knapweed does not reproduce vegetatively. Spotted knapweed is able to send lateral shoots below the soil surface that can form rosettes up to 3 cm from the parent plant (Watson and Renny 1974). Multiple rosettes on a single spotted knapweed root crown are common.

Allelopathy. The allelopathic compound, cnicin, has been isolated from diffuse and spotted knapweed leaves and shoots (Fletcher and Renny 1963). In vitro experiments show this chemical to reduce germination in crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.], bluebunch wheatgrass, and rough fescue (Kelsey and Locken 1987). In spring and fall soil samples, Kelsey and Locken (1987) found cnicin in soil samples collected in August only, and in a level not toxic in in vitro experiments. Later, they determined that the effects of resource competition were more important than allelopathy (Locken and Kelsey 1987).

Disturbance. Diffuse and spotted knapweed densities are correlated with the degree of soil disturbance. The greater the disturbance, the higher the density (Watson and Renny 1974). Once established, these weeds are able to form monotypic stands because their age class hierarchy allows them to occupy all available niches (Sheley and Larson 1996). Disturbance allows for rapid establishment and spread; however, both species are capable of invading well-managed rangelands (Lacey et al. 1990; Myers and Berube 1983; Tyser and Key 1988).

DIFFUSE AND SPOTTED KNAPWEED MANAGEMENT

Management Objectives. Land use objectives must be developed before diffuse and spotted knapweed management plans can be designed. In many cases, especially for large-scale infestations, strictly killing knapweeds is an inadequate objective. Sheley et al. (1996b) proposed that a generalized objective could be to develop an ecologically healthy plant community that is weed resistant and meets other land-use objectives such as livestock forage, wildlife habitat, or recreation. Once the desired plant community has been determined, an ecologically based integrated weed management strategy can be developed.

Integrated Weed Management. The magnitude and complexity of the diffuse and spotted knapweed problem indicates that successful management requires the adoption of integrated strategies. Integrated knapweed management involves the use of several techniques in a well-planned, coordinated, and ecologically based strategy to maintain desired plant communities, or shift plant communities to those that are desired (Sheley et al. 1996b). Inventory and mapping are the first phases of any integrated weed management program. The second phase includes prioritizing, choosing, and strategically implementing management techniques for a particular unit. The third phase is adopting proper grazing management practices as a portion of the integrated program. The integrated weed management program must fit into an overall range management plan.

Inventory and Mapping. The primary objective of weed inventory and mapping is to accurately identify and delineate lands infested with populations of unwanted plants (Cooksey and Sheley 1996). The goal is to record weed species present, areas infested, weed density, rangeland under threat of invasion, soil and range types, and other site factors pertinent to successful management of knapweed-infested rangeland. Information from an inventory should be incorporated into a map that shows the location, type, and size of knapweed infestations. Accurate mapping is critical in developing an integrated knapweed management program. An example of a weed survey and mapping system is provided by Cooksey and Sheley (1996).

Prevention. Preventing diffuse and spotted knapweeds from spreading onto adjacent rangeland is the most cost-effective management strategy. Weed seed dispersal can be limited by not driving vehicles through weed-infested areas when seeds are present, not grazing livestock in weed-infested areas during flowering and seeding or holding animals for 7 d before moving to uninfested areas, and using hay that is free of knapweed seeds (Sheley et al. 1996a). Knapweed spread can also be limited by detecting and eradicating weed introductions early, minimizing soil disturbance, and containing neighboring knapweed infestations (Sheley et al. 1996a). Bounty programs have been successfully used to encourage the early detection of diffuse and spotted knapweed in Montana.

Biological Control. Various natural enemies have been released as biological control agents for diffuse and spotted knapweeds (Table 1) (Rees et al. 1996). Most biocontrol techniques use insect larvae that damage the host root, shoot, leaf, or flower, resulting in reduced seed production. Two seedhead-feeding flies (*Urophora affinis* and *U. quadrifasciata*) are well established on diffuse and spotted knapweeds. These fly species lay their eggs inside the knapweed flower buds in June. Their larvae induce galls in the flower heads where they feed on the phloem, which can reduce seed production by as much as 50% (Story et al. 1989). Larvae of the moth, *Metzneria paucipundctella,* feed on the flowers and seeds of spotted knapweed and may reduce seed production by about 20% (Story et al. 1989).

Five root-mining insect species have been released on diffuse and spotted knapweeds. A root moth (*Agapeta zoegana*) and a root weevil (*Cyphocleonus achates*) have been observed to damage roots of spotted knapweed plants. The root beetle, *Sphenoptera jugoslavica,* has

Table 1. Current biological control insects released on diffuse and spotted knapweeds.

Agent	Common name	Weed attacked	Type of agent	States established
Agapeta zoegana	Sulphur knapweed moth or yellow-winged knapweed root moth	CENMA, CENDI[a]	Root-boring moth	MT, OR, WA
Banganstemus fausti	Broad-nosed seedhead weevil	CENMA, CENDI	Seedhead weevil	MT, OR, UT
Chaetorellia acrolophi	Knapweed peacock fly	CENMA	Seedhead weevil	MT, OR
Cyphocleonus achates	Knapweed root weevil	CENMA	Root-boring/gall weevil	CO, MT, OR, WA
Larinus minutus	Lesser knapweed flower weevil	CENMA, CENDI	Seedhead weevil	MT, OR, WA
Larinus obtusus	Blunt knapweed flower weevil	CENMA	Seedhead weevil	WA
Metzneria paucipunctella	Spotted knapweed seedhead moth	CENMA	Seedhead moth	ID, MT, OR, WA
Pelochrista medullana	Brown-winged root moth	CENMA, CENDI	Root-boring moth	Not established in United States
Pterolonche inspersa	Gray-winged root moth	CENDI	Root-boring moth	MT
Sptenoptera jugoslavica	Bronze knapweed root borer	CENDI	Root-boring/gall beetle	CA, ID, MT, OR, WA
Terellia virens	Green clearwing fly	CENMA	Seedhead fly	MT, OR
Urophora affinis	Banded gall fly	CENMA, CENDI	Seedhead fly	CA, ID, MT, OR, UT, WA
Urophora quadrifasciata	UV knapweed seedhead fly	CENMA, CENDI	Seedhead fly	ID, MT, OR, UT, WA

[a] WSSA-Bayer Code: CENMA—spotted knapweed, CENDI—diffuse knapweed.

been released on diffuse knapweed. Two other root moths, (*Pelochrista medullana* and *Pterolonche inspersa*), have been released in Montana. Distribution of biocontrol agents is currently underway.

In addition to insect biocontrol agents, there are fungal and bacterial pathogens that infect diffuse and spotted knapweeds. *Sclerotinia sclerotiorum* is a common soil fungus native to North America that infects diffuse and spotted knapweeds, which can cause wilt and death under some conditions and shift the competition balance to associated grasses (Ford 1989; Jacobs et al. 1996). Spotted knapweed is infected by the bacteria *Pseudomonas syringae* pv. *syringae* (Kearing and Nowierski 1997). Pathogens are often associated with insect injury to the plant.

Burning. A single, low intensity fire does not effectively control diffuse and spotted knapweeds because it is not hot enough to prevent resprouting from crowns or reestablishment from viable seeds in the soil (Renny and Hughes 1969). A single low intensity fire increased the cover and density of both weeds in northern Washington without altering the residual, desirable understory species (Sheley and Roché 1982). Similarly, spotted knapweed increased about sixfold within 2 yr after a controlled fire on a forested site in Montana. Fires may create the type of disturbance that promotes the colonization of knapweeds.

Herbicide efficacy on diffuse and spotted knapweeds may increase when applied after burning (Lacey et al. 1995). Picloram applied at 0.28 kg/ha provided 100% control of both weeds 2 yr after a postburning application (Sheley and Roché 1982). Interestingly, residual understory grass cover and density on burned plots increased over nonburned plots where picloram had been applied. The authors suggested that burning may have provided a flush of nutrients available to remaining desirable species.

Cultivation. A single, shallow (7 cm) cultivation was ineffective in controlling diffuse knapweed, especially if crowns were incompletely covered (Atkinson and Brink 1953; Popova 1960). Cultivation to 18 cm eliminated knapweed with subsequent vigorous grass growth (Popova 1960). However, Velagala (1996) found single cultivation to 20 cm increased spotted knapweed density over the control, but reduced spotted knapweed biomass 1 yr after treatment. In that study, cultivation enhanced the establishment of intermediate wheatgrass [*Elytriga intermedia* (Host) Nevski] seedlings.

Fertilization. Nitrogen fertilizer enhances spotted knapweed because spotted knapweed captures newly available resources before neighboring desirable species (Popova 1960; Story et al. 1989). In a 2-yr study, Sheley and Jacobs (1997) found that picloram plus fertilizer did not interact to affect either spotted knapweed density or grass yield. However, fertilizer applied at 32 plus 40 kg/ha of nitrogen and phosphorus, respectively, increased grass yield on those sites with a substantial grass understory.

Grazing. Spotted knapweed can tolerate defoliation. However, severe defoliation will reduce root, crown, and aboveground growth (Kennet et al. 1992). Low to moderate levels of grazing of spotted knapweed by cattle (*Bos taurus*), sheep, and goats (*Capra hircus*) have been observed in Montana. Cattle appear to prefer grasses over spotted or diffuse knapweed (Lacey et al. 1995). Although rosettes of the first year's growth are nutritious and edible, they are difficult for cattle to eat because they are closely appressed to the ground (Popova 1960). Mature knapweed plants are fibrous and coarse, which make them less desirable, and the rough flowering stems along with spines on the floral bracts can irritate grazing animals.

Controlled grazing duration and repeated grazing by sheep of spotted knapweed when associated grasses were dormant altered the age class distribution of spotted knapweed (i.e., fewer but older and larger plants) and reduced reproduction (Olson et al. 1997). Because of dormancy, there was minimal impact on associated grasses. Sheep consumed all 1-yr-old and a majority of 2-yr-old plants, suggesting that long-term grazing may provide control of spotted knapweed by limiting recruitment. Angora goats have been successfully used to control spotted knapweed on the Lee Metcalf National Wildlife Refuge in Montana (P. Gonzalez, personal communication).

Hand Pulling. Persistent and careful hand pulling can control diffuse and spotted knapweeds (Lacey et al. 1995). Since regrowth can occur from both crowns and viable seeds in the soil, entire plants must be removed before they produce seeds each year. Knapweed plants are best pulled when the soil is wet because the crown is more completely removed. Flowering plants should be transported offsite for disposal in a manner ensuring seeds are not dispersed.

Herbicides. Picloram, clopyralid (3,6-dichloro-2-pyridinecarboxylic acid), dicamba (3,6-dichloro-2-methoxybenzoic acid), and 2,4-D [(2,4-diclorophenoxy)acetic acid] effectively control diffuse and spotted knapweeds on rangeland. In an 8-yr study, Davis (1990) found picloram at 0.28 kg/ha provided nearly 100% spotted knapweed control for 3 to 5 yr. The period of control tends to be shorter on coarse soils or as precipitation increases (Lacey et al. 1995). Application timing does not affect control (C. Duncan and M. Halstvedt, personal communication). During the period of control, residual grasses increased by 200 to 700% (Davis 1990). Sheley and Jacobs (1997) found that controlling spotted knapweed with picloram increased grass yield by an average of 1,500 kg/ha, while providing nearly 100% control for 2 yr. Griffith and Lacey (1991) suggested that as site productivity, value of animal unit months, and rate of spotted knapweed spread to new areas increased, economic returns increased relative to picloram treatment costs. In contrast, picloram treatment became less cost-effective as knapweed use by cattle increased.

Clopyralid (0.27 kg/ha) and clopyralid (0.21 kg/ha) plus 2,4-D (1.12 kg/ha) provided spotted knapweed control similar to picloram when applied during bolt or bud growth stages (Lacey et al. 1995). Percent control declined to below 83% when this herbicide combination was applied at rosette, flowering, and after flowering growth stages.

Dicamba (1.12 kg/ha) and 2,4-D (2.24 kg/ha) provided inconsistent and short-term control of spotted and diffuse knapweeds (Lacey et al. 1995). For long-term control, these herbicides must be applied annually until the seedbank is depleted through attrition. Control with dicamba and 2,4-D was similar to that of clopyralid plus 2,4-D when applied at the bud stage, but lower than that of picloram 3 yr after application.

Mowing. Long-term effects of mowing on diffuse and spotted knapweed population densities are unknown. A single mowing at the bud growth stage reduced the number of stems that produced seeds from about 34 (control) to below $8/m^2$ on both species (Watson and Renny 1974). In that study, mowing at the flower stage reduced the number of flowering stems to $0.3/m^2$. Mowing at both the bud and flower stage did not have an additive effect. Watson and Renny (1974) also found that mowing at the flowering stage or both bud and flowering stages reduced the percent germination of the seeds formed. Secondary flowering, with capitula forming, was observed in diffuse knapweed populations. In a greenhouse study, some spotted knapweed plants produced flowers even though they were clipped monthly from June through September, suggesting the response of plants to mowing will vary with environmental conditions (Kennet et al. 1992).

Revegetation. In areas where residual plant species are absent, long-term control of diffuse and spotted knapweeds is unlikely because desirable species are not available to occupy niches opened by the control procedure (James 1992; Sheley et al. 1996b). In these areas, establishing competitive plants is essential for the successful management of knapweeds and the restoration of desirable plant communities. Revegetation with aggressive species has been shown to inhibit the reinvasion of knapweeds (Borman et al. 1991; Hubbard 1975; Larson and McInnis 1989). However, there is a lack of data on reliable and affordable revegetation methods.

Typically, revegetation of diffuse and spotted knapweed-infested rangeland involves late-fall cultivation, followed immediately by a dormant seeding of grass. Grass and knapweeds emerge the next spring; however, knapweeds usually emerge first. At that time, glyphosate [*N*-(phosphonomethyl)glycine] may be applied before grass seedlings emerge to control knapweed and downy brome (*Bromus tectorum* L.) seedlings. As long as there is adequate spring precipitation, both grass and knapweed seedlings survive. If grass seedlings survive until mid-summer, a reduced rate of 2,4-D or mowing can be applied to weaken knapweed plants. Mowing and/or 2,4-D applications may need repeating. Grass seedling establishment is enhanced by increasing seeding rate (Velagala et al. 1997). Although the species most effective for revegetation of diffuse and spotted knapweed-infested rangeland depends on site condition, we believe a healthy, weed-resistant plant community consists of a diverse group of species that occupies most of the niches (Sheley et al. 1996b).

ADOPTING PROPER GRAZING MANAGEMENT PRACTICES

On areas with a competitive grass stand, proper management ensures that grasses remain strong and vigorous, thereby minimizing knapweed encroachment. Proper grazing is essential to maintaining competitive desired plants. Sheley et al. (1997) found that a single moderate ($< 60\%$) grass defoliation did not enhance the invasion of diffuse knapweed into either a pristine bluebunch wheatgrass/needle-and-thread (*Stipa comata* Trin. & Rupr.) or a crested wheatgrass community. Spotted knapweed emergence and growth was enhanced by increasing Idaho fescue (*Festuca idahoensis* Elmer) defoliation over 60% (Jacobs and Sheley 1997). Increasing defoliation increased soil moisture availability to spotted knapweed. To minimize weed invasion, grazing systems should alter the season of use; rotate or combine livestock types and pastures, which allows grazed plants to recover before being regrazed; and promote litter accumulation (Sheley et al. 1996a, 1997).

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