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Spotted knapweed and grass response to herbicide treatments

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Abstract

Picloram at 0.28 kg ai ha^{-1}, clopyralid plus 2,4-D at 0.21 kg ai ha^{-1} plus 1.12 kg ai ha^{-1}, or dicamba plus 2,4-D at 0.56 kg ai ha^{-1} plus 1.12 kg ai ha^{-1} were applied to spotted knapweed (*Centaurea maculosa* Lam.) at the spring-rosette, bolt, bud, flower, or fall-rosette growth stages in 1991 on 2 sites in Montana. Treatments (3 herbicide treatments, 5 growth stages) were applied in a randomized-complete-block design and replicated 3 times at each site. Effects of herbicides on mature and seedling spotted knapweed density depended upon spotted knapweed growth stage at the time of application and the number of years after application. Picloram consistently reduced mature spotted knapweed density to low levels (<5 plants m^{-2}), regardless of growth stage, and its effect persisted through 1994. Clopyralid plus 2,4-D applied at the bolt or bud stage reduced spotted knapweed densities similar to that of picloram (95%) at the Avon site, while providing about 50% reduction in density 3 years after application at Missoula. This treatment may provide an alternative to picloram in environmentally sensitive areas. Dicamba plus 2,4-D was most effective when applied during the bud and bolt growth stages, and least effective when applied during the spring- and fall-rosette stages. In most situations, picloram and clopyralid plus 2,4-D provided greater control of spotted knapweed than dicamba plus 2,4-D. Herbicide treatments increased perennial grass biomass from 173 kg ha^{-1} in the nontreated controls to 494, 880, and 1,309 kg ha^{-1} for dicamba plus 2,4-D, clopyralid plus 2,4-D and picloram, respectively.

Key Words: Pasture and rangeland weed control, clopyralid, dicamba, picloram, 2,4-D, *Centaurea maculosa*

Resumen

En 1991, en dos sitios de Montana, se aplicaron los herbicidas picloram (0.28 kg ia ha^{-1}), clopiralid mas 2,4-D (0.21 kg ia ha^{-1}mas 1.12 kg ia ha^{-1}) y dicamba mas 2.4-D (0.56 kg ia ha-1 mas 1.12 kg ia ha^{-1}) a "Spotted knapweed" (*Centaurea maculosa* Lam.) en las etapas de desarrollo: roseta de primavera, aparición de tallos florales, yemas, flores, floración y roseta de otoño. Los tratamientos (3 herbicidas y 5 etapas de desarrollo) se aplicaron bajo un diseño experimental de Bloques completos al azar con 3 repeticiones en cada sitio. Los efectos de los herbicidas en la densidad de plantas maduras y plántulas de "Spotted knapweed" dependieron de la etapa de desarrollo en que se encontraba el "Spotted knapweed" al momento de la aplicación y del número de años después de la aplicación. El picloram redujo a niveles consistentemente bajos (<5 plantas m^{-2}) la densidad de plantas maduras de "Spotted knapweed', esto sin importar la etapa de desarrollo en la que se encontraban y el efecto persistió hasta 1994. En el sitio Avon, el clopiralid mas 2,4-D aplicado en las etapas de aparición de tallos florales o yemas redujo la densidad de "Spotted knapweed" en forma similar que el picloram (95%), en tanto que en el sitio de Missoula, después de 3 años de la aplicación, la redujo en 50%. Este tratamiento puede proveer una alternativa al picloram en áreas ambientalmente sensitivas. El dicamba mas 2,4-D fue mas efectivo cuando se aplico durante las etapas de aparición de yema y tallos florales y menos efectivo cuando se aplico durante los estados de roseta de primavera y otoño. En la mayoría de los casos picloram y clopiralid mas 2,4-D controlaron mejor el "Spotted knapweed" que dicamba mas 2,4-D. Los tratamientos de herbicidas incrementaron la biomasa de pastos perennes de 173 kg ha^{-1} en las áreas sin tratamiento a 494, 880, y 1,309 kg ha^{-1} cuando se aplico dicamba mas 2,4-D, clopiralid mas 2,4-D y picloram respectivamente.

Spotted knapweed (*Centaurea maculosa* Lam.), a short-lived perennial weed, was introduced to the Pacific Northwest from Eurasia about 1900 (Roché and Talbott 1986). Since its introduction, spotted knapweed has aggressively invaded rangeland and open canopy forest sites in the northern intermountain region (Lacey et al. 1992, Losensky 1987, Roché et al. 1986). More than 2.8 million ha in Montana and adjoining states and Canadian provinces are infested with spotted knapweed (Lacey 1989). This weed can form dense infestations that reduce vigor and diversity of native plants (Forcella and Harvey 1983, Tyser and Key 1988). Spotted knapweed reduces forage production from 60 to 90%, which causes economic losses to the livestock industry and impairs wildlife populations (Watson and Renney 1974, Bucher 1984, Bedunah and Carpenter 1989). Spotted knapweed costs the livestock industry $11 million each year in direct costs, and could cost the industry $155 million if allowed to spread to its potential ecological range in Montana (Hirsh and Leitch 1996).

Integrating biological, cultural, and chemical control methods will be necessary to effectively manage large infestations of spotted knapweed (Cuda et al. 1989, Sheley et al. 1996). At this time, biological control with insects, pathogens, and grazing animals

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Table 1. Average seasonal precipitation (cm) during the 4–year study (1991 to 1994) and long–term precipitation at a recording station located 6.4 km from the Missoula study site (Missoula WSO) and 24.1 km from the Avon study site (Ovando).

	1991		1992		1993		1994		4-yr Mean		Long term Average
Months	Msla[b]	Avon	Msla	Avon	Msla	Avon	Msla	Avon	Msla	Avon	Msla
						(cm)					
Jan–Mar	5.8	3.1	7.7	2.8	5.5	3.3	3.4	2.0	5.6	2.8	7.6
Apr–Jun	13.9	11.0	11.4	9.5	13.3	12.1	15.8	17.1	13.6	12.4	8.7
Jul–Sep	3.0	4.7	7.8	7.2	9.4	18.7	3.9	3.0	6.0	8.4	8.1
Oct–Dec	7.4	6.4	5.8	4.9	7.3	3.3	6.4	6.1	6.7	5.2	6.8
Total	30.1	24.9	32.7	24.1	35.5	37.4	29.5	28.2	31.9	28.8	31.2

[a]No long term data available for Avon study site.
[b]Msla=Missoula study site.

has shown limited success in reducing spotted knapweed density (Story 1992, Lacey et al. 1994, Olson et al. 1997). Mechanical treatments are restricted by soil type and terrain on many rangeland sites. Therefore, herbicides are a necessary component of most successful integrated weed management projects.

Previous studies of other perennial weeds, such as leafy spurge (*Euphorbia esula* L.) and Russian knapweed (*Acroptilon repens* L.) indicate that herbicide efficacy depends upon the growth stage at the time of application (Lym and Messersmith 1983, Whitson et al. 1993). Studies focusing on the effect of application timing on spotted knapweed control are limited. Whitson et al. (1986) reported that spotted knapweed could be controlled easily with either spring or fall herbicide applications. In another study, spotted knapweed control was similar 2 months after application when herbicides were applied at the bud or flower stage (Lym and Messersmith 1986). Early spring treatments using picloram, clopyralid plus 2,4-D, and dicamba plus 2,4-D are commonly recommended to control spotted knapweed and increase forage production (Harris and Cranston 1979, Lacey et al. 1992, Lacey 1985, Fay et al. 1995).

No long-term studies report the optimum timing of herbicide application to maximize spotted knapweed control and subsequent forage production. Specific objectives of this study were to evaluate spotted knapweed control using picloram, clopyralid plus 2,4-D, and dicamba plus 2,4-D, and to determine the optimum growth stage at which to apply herbicides to maximize spotted knapweed control and grass production.

Materials and Methods

Study Sites

This study was conducted near Missoula and Avon, Mont., from 1991 through 1994. The Avon site was located on native rangeland with a long-term grazing history of light to moderate use (0–50% utilization, annually). The area had not been grazed for 8 years prior to the study. The Missoula site was seeded with crested wheatgrass [*Agropyron cristatum* (L.) Gaertn.] during the 1940s and had not been grazed by livestock since the 1930s. Although neither site was grazed by domestic livestock during the study, some use by wildlife was noted.

The Avon site was located on a nearly level floodplain at 1455 m elevation. Soil was a Typic Haploboroll with a gravelly loam texture, 3.9% organic matter, and pH 5.8. The Missoula site was located on foothills at 975 m elevation with a northwest aspect. Soil was a Typic Argiboroll with a gravelly loam texture, 4.8% organic matter, and pH 6.2. Average seasonal precipitation during the 4-year study at both sites, and long-term precipitation near Missoula are presented in Table 1.

Rough fescue (*Festuca scabrella* Torr.), bluebunch wheatgrass [*Pseudoroegneria spicatum* (Prush) Love], prairie junegrass (*Koeleria cristata* (L.) Pers.), and Idaho fescue (*Festuca idahoensis* Elmer) were dominant grasses at Avon. Crested wheatgrass was the most abundant grass at the Missoula location. Spotted knapweed was the dominant forb at both locations, averaging 36 mature plants m^{-2} at each site.

Procedures

Herbicides were applied using a CO_2 backpack sprayer equipped with a 3.1-m, 6-nozzle spray boom, calibrated to deliver 168 liters ha^{-1}. Plot size was 3.1 by 9.1 m. Picloram was applied at 0.28 kg active ingredients (ai) ha^{-1}, clopyralid plus 2,4-D at 0.21 kg ai ha^{-1} plus 1.12 kg ai ha^{-1}, and dicamba plus 2,4-D at 0.56 kg ai ha^{-1} plus 1.12 kg ai ha^{-1}. Applications were made when spotted knapweed was at the spring-rosette, bolt, bud, flower, or fall-rosette growth stage during 1991 (Table 2). Treatments (3 herbicide treatments, 5 growth stages) were applied in a randomized--complete-block design and replicated 3 times at each site.

Sampling

Spotted knapweed density was determined in 3 randomly located 0.25-m^2 quadrants per plot during flowering in 1992, 1993, and 1994. Spotted knapweed

Table 2. Five phenological stages of spotted knapweed and dates of herbicide application at 2 study sites in western Montana.

Spotted knapweed growth stage	Growth stage description	Herbicide application date Missoula	Avon
Rosette	plants 50–150 mm diamter	12 May 1991	17 May 1991
Bolt	85% of plants @125–230 mm bolt 15% of plants @ 50–125 mm bolt	7 June 1991	11 June 1991
Bud	75% of plants @ mid–bud stage 25% of plants @ early-bud stage	25 June 1991	3 July 1991
Flower	mid–flower stage; 90% of plants flowering	1 Aug. 1991	3 Aug. 1991
Fall regrowth	basal rosettes expanded to 50–150 mm diameter	12 Sept. 1991	12 Sept. 1991

plants were categorized as seedlings (defined as those that germinated during the current growing season and had 1 to 5 leaves) or mature plants (defined as those that had been growing for more than a season and had more than 5 leaves). Above-ground perennial grass biomass was harvested at peak standing crop during the third growing season following application. Plant material was clipped to a height of 1 cm within the 0.25-m^2 quadrats after spotted knapweed density had been determined. Samples were dried in a ventilated, heated (45°C) room to a constant weight (168 hours) and weighed. Perennial grasses were not separated by species during sampling because the objective was to determine overall response of perennial grasses to herbicide treatments.

Analysis

All data were pooled and analyzed using analyses of variance. Site differences were detected; therefore, each site was analyzed separately. The model used for determining treatment differences in spotted knapweed density was a split-plot in time with herbicide treatment, growth stage, and herbicide treatment by growth stage tested using replication by herbicide treatment by growth stage as the error term. Year, year by herbicide treatment, year by growth stage, year by herbicide treatment by growth stage were analyzed as whole-plots. Biomass data were analyzed as a randomized-complete-block design. Herbicide treatment and growth stage at time of application were main effects. Herbicide by growth stage interaction was included in the model. All other sources of variation were pooled into the error term. Mean separations were made using

Table 3. Mean squares generated from analysis of variance of spotted knapweed density data.

		Mean square			
		Missoula		Avon	
Source of variation	Df	Mature	Seedlings	Mature	Seedlings
Rep	2	525	178326	48	20267
Herb	3	26868**	4038920**	10638**	1490652**
Stage	4	3091**	485239**	302**	38005**
Herb * Stage	12	2080**	193600**	272**	21639**
Error A	38	3040	63215	50**	11806
Year	2	2002**	1022605**	1275**	72193**
Year * Herb	6	401*	67794**	360**	33598**
Year * Stage	8	151	20457	28	7502
Year * Herb * Stage	24	1090	33743**	69**	7625
Error B	80	30	15764	22	7072

[a] *, ** significant at the 5% and 1% levels of probability, respectively.

Fisher's protected LSD's at P=0.05 (Peterson 1985).

Results

Mature Spotted Knapweed Density

At Missoula, analysis of variance indicated that the effect of herbicide treatments on mature spotted knapweed density depended upon the growth stage at which the herbicides were applied (Table 3). Applied at the spring-rosette stage, picloram and clopyralid plus 2,4-D reduced the number of mature spotted knapweed plants similarly for 3 years following treatment (Fig. 1). Dicamba plus 2,4-D reduced spotted knapweed density to about 50% compared to the control, but knapweed density was about 4 times greater than in plots sprayed with either picloram or clopyralid plus 2,4-D. Treatments applied at the bolt growth stage yielded similar densities to those applied at the spring-rosette growth stage, except that dicamba plus 2,4-D reduced spotted knapweed density to about 5 plants m^{-2}. This was similar to results of the clopyralid plus 2,4-D and picloram treatments. All herbicide treatments reduced mature spotted knapweed plant density similarly when applied at the bud growth stage. Picloram applied at the flower and fall-rosette growth stage yielded lowest spotted knapweed density at those stages. Clopyralid plus 2,4-D and dicamba plus 2,4-D yielded similar mature spotted knapweed densities at these growth stages. All herbicide treatments reduced spotted knapweed density below that of the control, regardless of growth stage at the time of application.

At Missoula, analysis of variance also indicated that the effect of herbicides on the density of mature spotted knapweed depended upon the year after application (Table 3). Picloram and clopyralid plus 2,4-D yielded the lowest mature spotted knapweed density in 1992 (Fig. 2). Dicamba plus 2,4-D reduced spotted knapweed density 3 times lower than that of

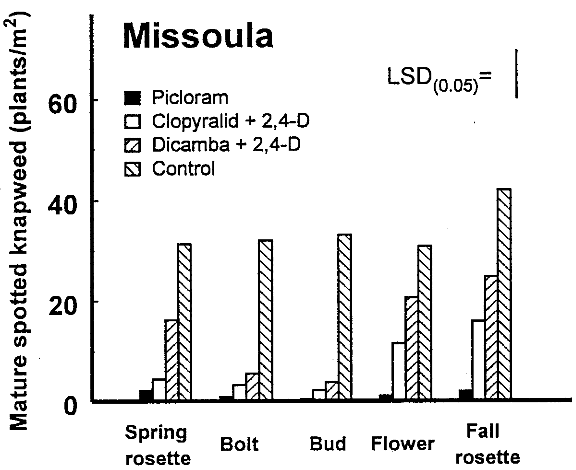

Fig. 1. Effect of herbicides applied at 5 growth stages on mature spotted knapweed at Missoula.

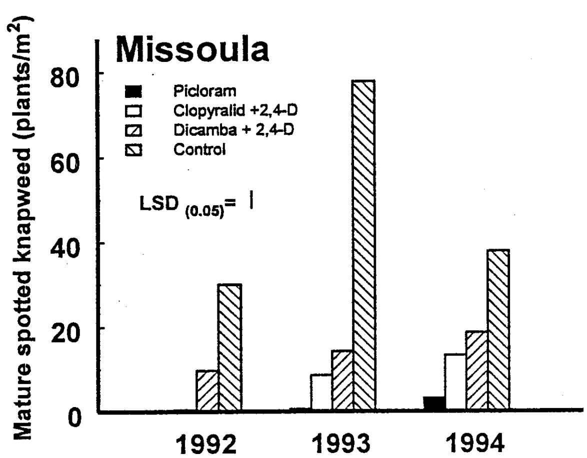

Fig. 2. Effect of herbicides each year following application on mature spotted knapweed at Missoula.

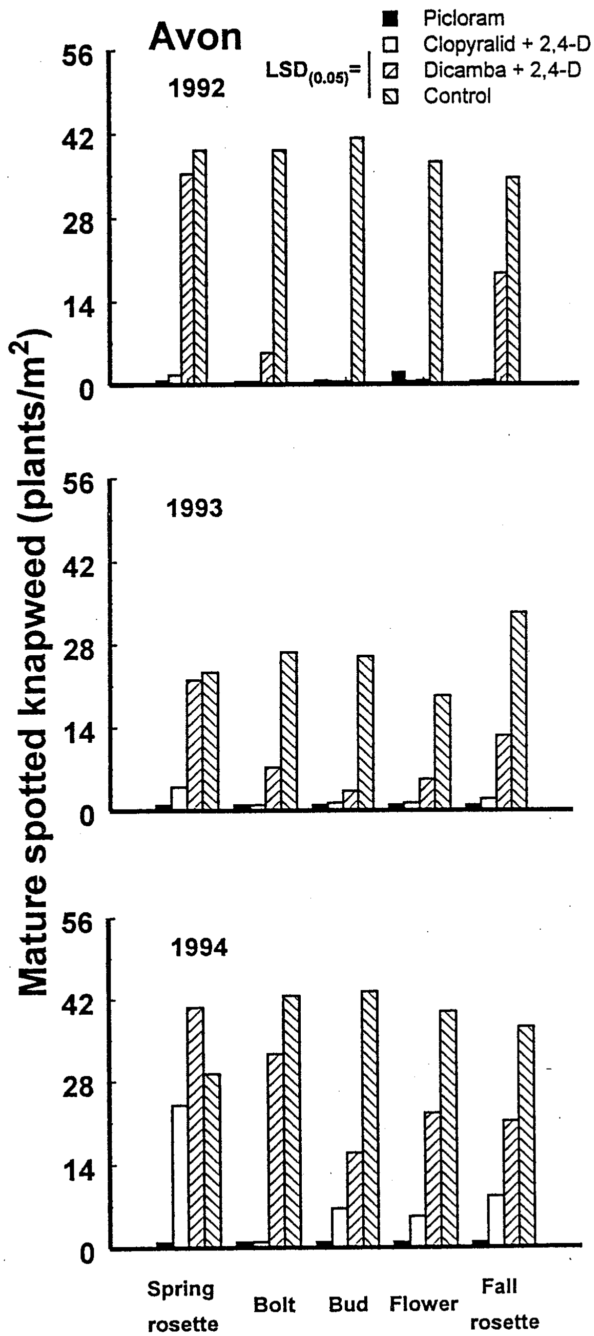

Fig. 3. Effect of herbicides applied at 5 growth stages on mature spotted knapweed in 1992, 1993, and 1994 at Avon. Comparisons can be made within or among bargraphs.

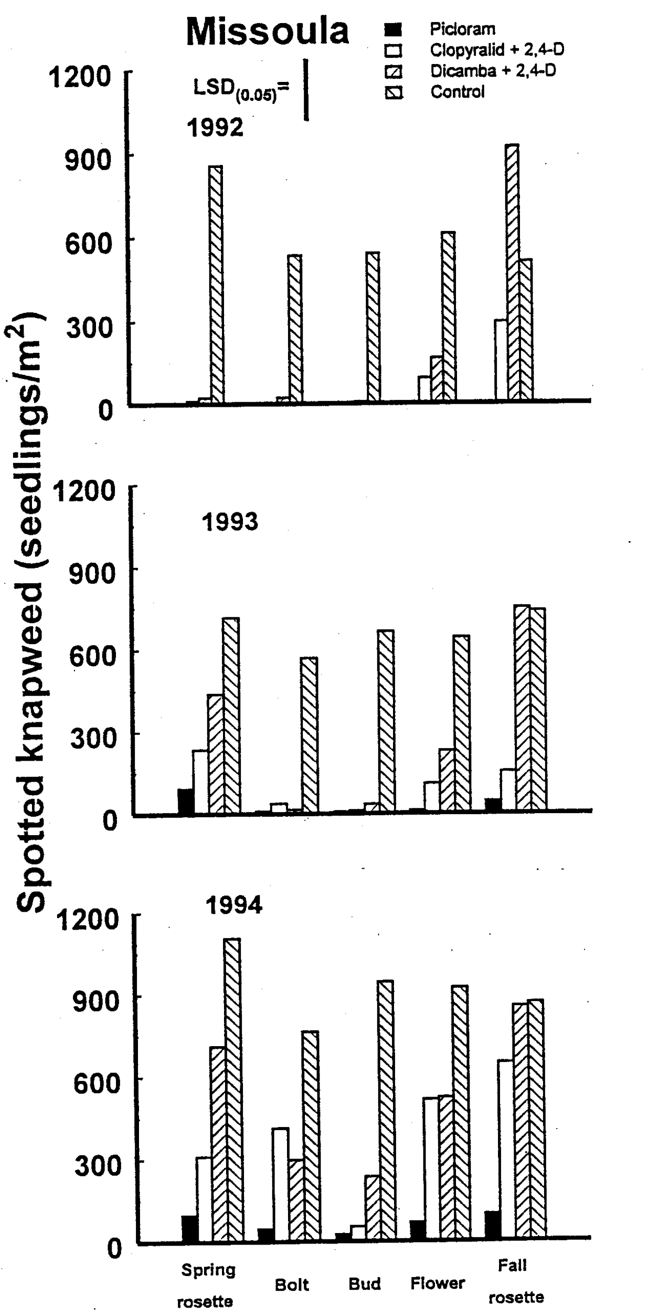

Fig. 4. Effect of herbicides applied at 5 growth stages on spotted knapweed seedlings in 1992, 1993, and 1994. Comparisons can be made within or among bargraphs.

the control that year. In 1993 and 1994, picloram yielded the lowest spotted knapweed density. Spotted knapweed density in plots treated with clopyralid plus 2,4-D was about 8.5 and 13 plants m^{-2}, while its density in plots treated with dicamba plus 2,4-D was about 14 and 19 plants m^{-2} in 1993 and 1994, respectively. All herbicide treatments reduced spotted knapweed density below that of the control, through the third year after application. At Avon, effect of the herbicide treatments on mature spotted knapweed density depended on the weeds growth stage and the number of years after application (Table 3). During each year and growth stage, picloram yielded nearly complete reduction of spotted knapweed density (Fig. 3). In 1992 and 1993, clopyralid plus 2,4-D reduced spotted knapweed density similarly to that of picloram at all growth stages. By 1994, only the bolting stage application of clopyralid plus 2,4-D remained as effective as picloram. This herbicide treatment was least effective when applied during the spring-rosette growth stage and moderately effective at the bud, flower, and fall-rosette growth stages by end of the study. In 1992, dicamba plus 2,4-D yielded nearly complete reduction of mature spotted knapweed density when applied at the bud and flower growth stages at Avon (Fig. 3). After treatment at these growth stages, spotted knapweed density increased as years after application increased. Among the dicamba plus 2,4-D treatments, the bud stage application yielded the lowest mature spotted knapweed density in 1994. Application of dicamba plus 2,4-D at the bolt growth stage reduced spotted knapweed density to about 4 plant m^{-2} in 1992, but the weed rapidly reestablished after this treatment. Dicamba plus 2,4-D applied at the fall-rosette growth stage reduced spotted knapweed density from about 35 to 20, 12, and 24 plants m^{-2} in 1992, 1993, and 1994, respectively. Of the herbicide treatments, dicamba plus 2,4-D applied at the spring-rosette growth stage was the least effective in reducing mature spotted knapweed density.

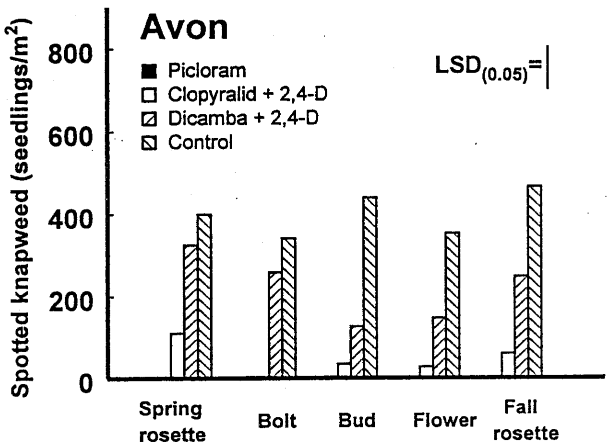

Fig. 5. Effect of herbicides applied at 5 growth stages on spotted knapweed seedlings at Avon.

Spotted Knapweed Seedling Density

At Missoula, effect of herbicide treatment on seedling spotted knapweed density depended upon growth stage and the time elapsed since application (Table 3). In 1992, picloram, clopyralid plus 2,4-D, and dicamba plus 2,4-D applied at the spring-rosette, bolt, bud, or flower growth stage provided similar seedling density reduction (Fig. 4). Picloram eliminated spotted knapweed seedlings for a full year when applied at the fall-rosette growth stage. Clopyralid plus 2,4-D and dicamba plus 2,4-D applied during the fall-rosette growth stage had seedling densities of 225 and 900 plant m^{-2}, respectively, in 1992. In 1993, all 3 herbicide treatments provided similar density reduction, with the exception of dicamba plus 2,4-D applied at the spring-and fall-rosette growth stage. Dicamba plus 2,4-D applied in the spring-rosette growth stage yielded about 450 plants m^{-2}, which was similar to that of clopyralid plus 2,4-D applied at the same stage that year. Dicamba plus 2,4-D applied at the fall-rosette growth stage yielded seedling densities similar to that of the control in 1993. By 1994, picloram and clopyralid plus 2,4-D yielded lowest seedling spotted knapweed density when applied at the spring-rosette growth stage. Dicamba plus 2,4-D reduced seedling densities of spotted knapweed by about 400 plant m^{-2} below that of the control applied at this growth stage. Applied at the bolt growth stage, picloram yielded the lowest number of spotted knapweed seedlings in 1994. Clopyralid plus 2,4-D and dicamba plus 2,4-D reduced spotted knapweed seedling density by about 50% at that time. In 1994, all 3 herbicide treatments yielded similar densities when applied at the bud growth stage. Applied at the flower and fall-rosette growth stages, picloram yielded the lowest seedling densities. Clopyralid plus 2,4-D applied at the flower growth stage reduced seedling spotted knapweed densities by about 50% of the control, but the herbicides effect was removed by 1994 when applied at the fall-rosette growth stage.

At Avon, analysis of variance indicated that the effect of herbicide treatments on spotted knapweed seedling density depended upon growth stage at which the herbicides were applied (Table 3). Picloram applied at any growth stage and clopyralid plus 2,4-D applied at bolt, bud, flower, and fall-rosette growth stages provided lowest spotted knapweed seedling density (Fig. 5). Clopyralid plus 2,4-D applied at the rosette growth stage lowered spotted knapweed seedling density to about 110 plants m^{-2}. Dicamba plus 2,4-D did not reduce spotted knapweed seedling densities when applied at the spring-rosette or bolt growth stage. At all other growth stages, dicamba plus 2,4-D yielded densities ranging from 120 to 250 seedling m^{-2}.

At Avon, analysis of variance also indicated the effect of herbicide treatment on spotted knapweed seedling density depended upon the year after application (Table 3). Picloram (0 seedlings m^{-2})and clopyralid plus 2,4-D (50 seedlings m^{-2}) yielded lowest spotted knapweed seedling density all three years after application (Fig. 6). Dicamba plus 2,4-D yielded 239, 265, and 159 seedling spotted knapweed plants m^{-2} in 1992, 1993, and 1994, respectively. All herbicide treatments reduced seedling spotted knapweed density below that of the control at this site.

Grass biomass

At the Missoula site, the effect of herbicide treatment on grass biomass 3 years after application depended upon the growth stage of spotted knapweed at the time of application (Table 4). Applied at the spring-rosette growth stage, picloram and clopyralid plus 2,4-D yielded greatest grass biomass, while dicamba plus 2,4-D yielded least grass biomass (Fig. 7). Applied at the bolt growth stage, picloram yielded highest grass biomass. Clopyralid plus 2,4-D (610 kg ha^{-1}) and dicamba plus 2,4-D (590 kg ha^{-1}) yielded similar grass biomass at that growth stage. Picloram and clopyralid plus 2,4-D yielded highest bio-

Table. 4. Means squares generated from analysis of variance of biomass data.

Source	Df	Mean square Missoula Biomass	Avon Biomass
Rep	2	4077739.0	548844.2
Herb	3	3999166.9**[a]	5139628.9*
Stage	4	565234.1 **	216856.2
Herb * Stage	12	148020.1**	132272.3
Error	38	68109.9	98702.0

[a,**] significant at the 5% and 1% levels of probability, respectively.

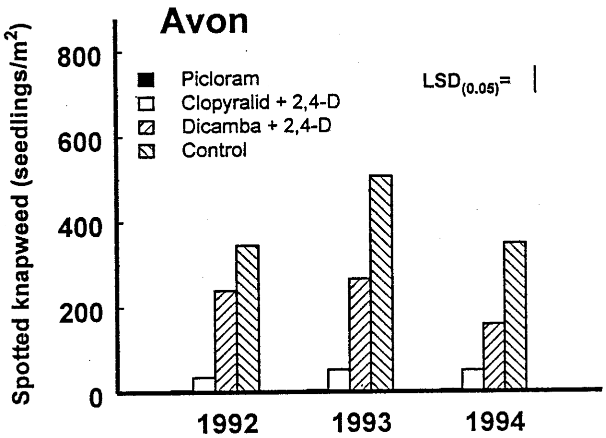

Fig. 6. Effect of herbicides each year following application on spotted knapweed seedlings at Avon.

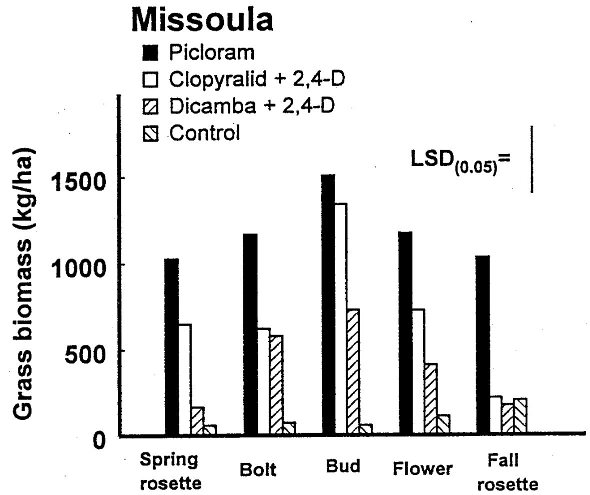

Fig. 7. Effect of herbicides applied at 5 growth stages on perennial grass biomass at Missoula.

mass, but was similar to picloram applied at the bolt and flower growth stages. Dicamba plus 2,4-D applied at the bud growth stage yielded about 750 kg/ha^{-1} of grass, which was about 10 times that of the control. Picloram and clopyralid plus 2,4-D yielded highest grass biomass when applied at the flower growth stage; however, clopyralid plus 2,4-D yielded grass biomass similar to that of dicamba plus 2,4-D at this growth stage. Dicamba plus 2,4-D did not increase grass yields over those of the control. Applied at the fall-rosette growth stage, picloram yielded highest grass biomass. All other herbicide treatments were similar to the control when applied at this stage.

Herbicide treatments affected grass biomass at Avon and was not dependent upon growth stage (Table 4). Picloram, clopyralid plus 2,4-D, and dicamba plus 2,4-D yielded 1600, 1175, and 620 kg ha^{-1} of grass biomass, respectively (Fig. 8). All herbicide treatments produced greater biomass than that of the control.

Discussion

Picloram provides consistent and effective control of spotted knapweed. Davis (1990) found that picloram applied at 0.07, 0.11, 0.14, 0.22, 0.25, and 0.28 kg ai ha^{-1} during the bud growth stage provided 100% control for 3 to 5 years. In this 4-year study, we found that the efficacy and persistence of spotted knapweed control using picloram at 0.28 kg ai ha^{-1} was independent of the weeds growth stage and the time of application. Based on our study, we concluded that spotted knapweed re-establishes from its seedbank, rather than regrowth from mature plants. Spotted knapweed seeds remain dormant, but viable in the soil for over 8 years (Davis et al. 1993).

In many situations, land managers apply picloram when they notice the flowering plants. Unfortunately, this may be the least effective method of determining timing of herbicide applications. In this case, knapweed plants continue to produce seeds after picloram has been applied, but before the plants die. This replenishes the seedbank and results in continuous, periodic picloram applications, which are probably not cost effective (Griffith and Lacey 1991). Applying picloram before flowers appear may prevent spotted knapweed seed rain and reduce the seedbank. Over a long period (>10 years), spotted knapweed density may be reduced to occasional plants or patches, which can be retreated by spot spraying. An alternative method for determining timing of repeated application would be to identify threshold levels of spotted knapweed that would optimize the value of the application based of the response of the desired plant community.

Clopyralid plus 2,4-D (0.21 kg ai ha^{-1} plus 1.12 kg ai ha^{-1}) applied at the bolt or bud stage provided control of spotted knapweed similar to picloram (about 95% control) at Avon and about 50% control 3 years after application at Missoula. Fay (1990) found clopyralid plus 2,4-D at similar rates provided nearly 100% control of spotted knapweed 1 year following application on 2 sites in Montana. Clopyralid has a shorter soil residue period and adsorbs to soil particles more tightly than picloram (Fay et al. 1991). In addition, clopyralid plus 2,4-D may maintain greater species diversity than picloram (Rice et al. 1992). Therefore, clopyralid plus 2,4-D may provide an alternative to picloram in environmentally sensitive areas.

Dicamba is more effective in controlling spotted knapweed than 2,4-D because it provides 2 to 3 years of control depending on the level of plant competition following treatment (Fay et al. 1989). In another study, dicamba at 2.2 kg ai ha^{-1} provided excellent control when applied in the rosette growth stage (Lacey et al. 1986). In our study, dicamba plus 2,4-D (0.56 plus 1.12 kg ai ha^{-1}) was most effective when applied during bolt and bud growth stages, and least effective during the spring-and fall-rosette growth stage. However, clopyralid plus 2,4-D provided greater control

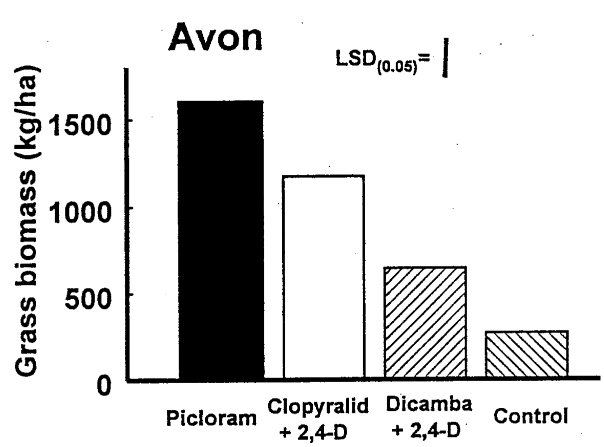

Fig. 8. Effect of herbicides on grass biomass at Avon.

than dicamba plus 2,4-D at those stages. Dicamba plus 2,4-D is currently recommended for controlling spotted knapweed on small ranchettes (about 44 ha) because the combination provides good control, but is not persistent enough to limit landowners' options in the future (Fay et al. 1995). This study suggests that clopyralid plus 2,4-D may provide more effective and longer-term spotted knapweed control without greatly limiting future land management options.

Although picloram persists in the soil and affects weeds for 12 to 30 months (Hamaker et al. 1967, Lacey 1985), extended control is enhanced by competition from residual perennial grasses that are released from competition by the herbicide application (Renney and Hughes 1969). In most cases, picloram yielded highest grass biomass 3 years after treatment, which may help explain the persistence of control of spotted knapweed using this herbicide. Picloram increased grass biomass by 1,000 to 1,550 kg ha^{-1}. These results were similar to those found by Davis (1990) and Sheley and Jacobs (1997). Long-term herbicidal control of spotted knapweed using picloram can be cost-effective on cattle ranches with highly productive rangeland and a residual (suppressed) grass understory (Griffith and Lacey 1991). However, future research should focus on incorporating picloram and other herbicides into effective and sustainable integrated weed management strategies.

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