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Enhancing intermediate wheatgrass establishment in spotted knapweed infested rangeland

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Abstract

The objective of this study was to compare intermediate wheatgrass establishment at 4 seeding rates, in combination with tillage and/or glyphosate (n-phosphomethyl glyine), in spotted knapweed infested rangeland. We hypothesized that the establishment of intermediate wheatgrass seedlings would be greatest at high seeding rates, while spotted knapweed density and biomass would be negatively impacted by intermediate wheatgrass densities. Glyphosate (1.16 liters a.i./ha; with and without), tillage (200 mm depth; with and without), and 4 seeding rates (0, 500, 2,500, 12,500 m^{-2}) of intermediate wheatgrass seeds were factorially arranged in a randomized-complete-block design with 4 blocks at each of 2 sites in Montana. Treatments were applied in the fall of 1995. By the second growing season, intermediate wheatgrass failed to established in plots seeded with 500 seeds m^{-2}, the currently recommended seeding rate. Increasing the seeding rate to 2,500 and 12,500 m^{-2} increased intermediate wheatgrass tiller density by 80 and 140 plants m^{-2}, respectively, at Hamilton and 158 and 710 plants m^{-2}, respectively, at Bozeman. At the highest seeding rate, combining tillage with glyphosate increased tiller density over 3 times more than other treatments where intermediate wheatgrass successfully established at Hamilton. However, neither tillage nor glyphosate affected intermediate wheatgrass density at Bozeman by the second growing season. In the first season, seeding rates of 0, 500, 2,500, 12,500 m^{-2} produced 214, 208, 176, and 114 knapweed plants m^{-2}, respectively ($LSD_{0.05}$=36.1) at Bozeman, but had no effect at Hamilton. Our revegetation study suggests that increasing intermediate wheatgrass seeding rates can facilitate their establishment in spotted knapweed infested rangeland. Using high seeding rates to control spotted knapweed and increase seedling establishment may enhance our ability to use revegetation as an effective weed management strategy.

Key Words: *Centaurea maculosa*, *Bromus tectorum*, *Elytriga intermedia*, revegetation, tillage, glyphosate, seedling establishment.

Resumen

El objetivo de este estudio fue comparar el establecimiento dé intermediate wheatgrass (*Elytriga intermedia (Host) Nevski*) en 4 dósis de siembra, en combinación con preparación de suelo y/o glyphosate (n-phosphomethyl glyine), en praderas infestadas con spotted knapweed (*Centaurea maculosa* Lam.) Formulamos una hipótesis, la cual suponía que el establecimiento de plántulas de intermediate wheatgrass alcanzarían sus niveles más altos a niveles altos de siembra, mientras la densidad y biomasa de spotted knapweed mostrarían un impacto negativo según las densidades de intermediate wheatgrass. Glyphosate (1.16 litros a.i./ha; con y sin), preparadión de suelo (a 200 mm de profundidad, con y sin y 4 dósis de siembra (0, 500, 2,500 y 12,500 m^{2}) de semillas de intermediate wheatgrass fueron arreglados factorialmente en un diseño de bloques completamente al azar, con 4 bloques ubicados en cada uno de los dos sitios en Montana. Se aplicaron los tratamientos en el otoño de 1995. Para la segunda temporada de cultivo, intermediate wheatgrass no pudo establecerse en las parcelas sembradas con 500 semillas m^{-2}, el nivel de siembra que se recomienda actualmente. Aumentando el nivel de la siembra a 2,500 y a 12,500 m^{-2} aumentó la densidad de rebrotes de intermediate wheatgrass en 80 y 140 plantas m^{-2} respectivamente, en Hamilton y en 158 y 710 plantas m^{-2} respectivamente, en Bozeman. Al nivel más alto de dósis de siembra, la combinación de preparación de suelo con glyphosate aumentó la densidad de rebrotes en exceso de 3 veces más que en otros tratamientos y en los cuales intermediate wheatgrass tuvo Èxito en establecerse en Hamilton. Sin embargo, para la segunda temporada de cultivo, ni la preparación de suelo ni glyphosate afectaron la densidad de intermediate wheatgrass en Bozeman. Durante la primera temporada de cultivo, dósis de siembra de 0, 500, 2,500 y 12,500 m^{-2} produjeron 214, 208, 176, 114 plantas m^{-2} de spotted knapweed, respectivamente (LSD = 36.1) en Bozeman, pero no causaron ningún efecto en Hamilton. Nuestro estudio de revegetación sugiere que al aumentar las dósis de siembra de intermediate wheatgrass, se puede facilitar su establecimento en praderas infestadas con spotted knapweed. Es posible que el uso de niveles altos de siembra para controlar spotted knapweed e incrementar el establecimiento de plántulas pueda mejorar nuestra capacidad de utilizar la regegetación como estrategia eficaz en el control de malezas.

Spotted knapweed (*Centaurea maculosa* Lam.), a deep-taprooted perennial weed of Eurasian origin, has been

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expanding its range throughout the northwestern United States and Canada since the late-1800s (Watson and Renney 1974, Harris and Cranston 1979, Strang et al. 1979, Roché and Talbott 1986). This invasive weed has been spreading at about 27% per year since 1920 (Chicoine et al. 1985). It is estimated that spotted knapweed infests about 2.2 million hectares of grassland in Montana (Lacey et al. 1989) and about 10,000 hectares in both eastern Washington (Roché 1988) and British Columbia (Cranston 1988). Spotted knapweed reduces forage production (Watson and Renney 1974, Harris and Cranston 1979), species richness (Tyser and Key 1988), and wildlife habitat (Bedunah and Carpenter 1989). Increases in bare-ground (Tyser and Key 1988), surface water runoff and stream sedimentation (Lacey et al. 1989), and management costs are also associated with knapweed *(Centaurea* spp.) infestations.

Spotted knapweed control is often short-term if desirable species are not available to occupy safe sites opened by the control procedure (James 1992, Sheley et al. 1996). In these areas, introducing and establishing competitive plants is essential for successful management of spotted knapweed and the restoration of desirable plant communities (Hubbard 1975, Larson and McInnis 1989, Borman et al. 1991). Seedling establishment appears associated with the availability of safe sites (Harper et al. 1965, Wright et al. 1978) and the availability of seeds (Pickett et al. 1987). Rehabilitating knapweed infested rangeland with desirable grasses typically fails, however, because of competition with weeds for safe sites during the initial stages of establishment (Borman et al. 1991, James 1992). In addition, density-dependent (competition) and density independent factors interact to determine seedling survival during intermediate wheatgrass (*Elytriga intermedia* (Host) Nevski) establishment in spotted knapweed infested rangeland (Velagala et al. 1997).

Density of desired plants may influence weed competition during the initial stages of establishment. In a growth chamber, Jacobs et al. (1996) found that bluebunch wheatgrass (*Pseudoroegneria spicata* (Pursh.) Löve) was 4 times more competitive than spotted knapweed seedlings at densities (1,000–5,000 plants m^{-2}) higher than normal for rangeland revegetation. Similarly, Velagala et al. (1997) found that increasing intermediate wheatgrass from <1,000 plants m^{-2} to >1,000 plants m^{-2} removed the competitive effect of spotted knapweed on intermediate wheatgrass biomass where interspecific interference occurred.

The objective of this study was to determine whether extraordinarily high seeding rates could be used to facilitate the initial establishment of intermediate wheatgrass in spotted knapweed infested rangeland. We compared intermediate wheatgrass density and biomass at 4 seeding rates in combination with tillage and glyphosate (n-phosphomethyl glyine). We hypothesized that the establishment of intermediate wheatgrass seedlings would be greatest at high seeding rates, control procedures that increase the availability of safe sites would increase wheatgrass establishment, and spotted knapweed density and biomass would be negatively impacted by wheatgrass densities.

Materials and Methods

Study Sites

The study was conducted during 1995, 1996, and 1997 about 11 km east-northeast of Hamilton, Mont. (46° 17' N, 114° 1' W) at an elevation of 1,341 m and about 15 km southwest of Bozeman, Mont. (45° 36' N, 111° 11' W) at an elevation of 1,524 m. The Hamilton site is a *Festuca scabrella/ Pseudoroegneria spicata* habitat type and the Bozeman site is a *Festuca idahoensis/Pseudoroegneria spicata* habitat type (Mueggler and Stewart 1980). Both sites were dominated by spotted knapweed and cheatgrass (*Bromus tectorum* L.), with very few other species present. Hamilton soils were Stecum stony loamy coarse sand (mixed typic Cryorthenths) and were moderately deep. Bozeman soils were loamy-skeletal over sandy or sandy skeletal (mixed typic Argiboroll). Annual precipitation at both sites ranges from 406 to 457 mm with a bimodal distribution with peaks in the winter and spring. The mean annual temperature at Hamilton is 6.6°C and 6.1°C at Bozeman. Precipitation and temperature were monitored within 6.5 km of each site. During the period of the study, precipitation and temperature were near the long-term average (Table 1).

Table 1. Seasonal summary of precipitation and temperature at Hamilton and Bozeman Montana during the period of the study.

Site	Year	Period	Total precipitation	Mean temperature Max	Min
			(mm)	(˚C)	
Hamilton	1995	Fall	84	5.2	-3.5
	1996	Winter	63	4.4	-6.8
	1996	Spring	141	18.3	4.1
	1996	Summer	69	26.9	7.3
	1996	Fall	121	6.8	-7.1
	1997	Winter	65	4.5	-8.5
	1997	Spring	194	18.0	3.1
	1997	Summer	96	26.5	9.2
Bozeman	1995	Fall	46	6.3	2.8
	1996	Winter	50	2.7	-10.1
	1996	Spring	167	18.2	3.1
	1996	Summer	59	26.4	8.9
	1996	Fall	1215	7.8	-1.1
	1997	Winter	59	5.3	-5.0
	1997	Spring	133	16.6	4.2
	1997	Summer	34	27.9	9.5

Environmental conditions were monitored daily. Precipitation amounts are monthly cumulative values. Maximum and minimum temperatures are means for the designated period.

Procedures

Glyphosate (with and without), tillage (with and without), and 4 seeding rates (0, 500, 2,500, 12,500 m^{-2}) of intermediate wheatgrass seeds were factorially applied in a randomized-complete-block design with 4 blocks (replications) at each site (128 total plots). Glyphosate, a non-selective herbicide, which is rapidly deactivated by binding to soil particles, was applied at 1.16 liters a.i./ha using a CO_2 pressurized backpack sprayer calibrated to deliver a total volume of 410 liter ha^{-1}. Tillage was accomplished using a tractor mounted rototiller that mixed the soil to a depth of about 200 mm. Seeds of 'Oahe' intermediate wheatgrass were broadcast on the soil surface of each plot (1.82 m^2) immediately after application and were covered with a small amount of soil (< 2 mm). Intermediate wheatgrass seeds were purchased from Circle S Seeds Inc., Three Forks, Mont. in October 1995. Intermediate wheatgrass is an important grass species used for revegetating spotted knapweed infested rangeland on these habitat types (Holzworth and Lacey 1991). Ninety-four percent of the seeds germinated in a standard test (Wiesner 1991). Treatments were applied during November 4 through 8 November 1995 at Bozeman, and 11 November through 14 November 1995 at Hamilton.

Sampling

The study was sampled at peak standing crop (July) in 1996 and 1997. Density of intermediate wheatgrass, spotted knapweed, and cheatgrass were determined by counting the number of plants in a randomly placed 0.44 m^2 circular hoop in each plot. Biomass was determined by clipping plants to ground level. Plants were separated by species, dried (60°C, 48 hr) to a constant weight, and weighed.

Analysis

Analysis of variance was used to determine the effects of intermediate wheatgrass seeding rate, tillage, and glyphosate on density and biomass of intermediate wheatgrass, spotted knapweed, and cheatgrass. Initial analysis of variance included site, year, seeding rate, tillage, glyphosate, and their factorial combinations in the model. This analysis indicated the presence of 4- and 5-way interactions. Therefore, sites and years were analyzed separately. Seeding rate, tillage, glyphosate, seeding rate*tillage, seeding rate*glyphosate, tillage*glyphosate, and seeding rate*tillage*glyphosate were included in the model. Pr ≤ F values are presented to separate significant ($\alpha = 0.05$) main effect means for tillage and glyphosate. Mean separations for significant seeding rate and interactions were achieved using Fisher's protected LSD ($P \leq 0.05$) comparisons (Peterson 1985).

Results

Intermediate wheatgrass

Hamilton

Analysis of variance indicated seeding rate*tillage (1996) and seeding rate*tillage*glyphosate (1997) interacted to affect intermediate wheatgrass tiller density at Hamilton (Table 2). In 1996, unseeded plots and those seeded at rates of 500 m^{-2} yielded similar wheatgrass density, regardless of tillage (Fig. 1). Seeding at 2,500 m^{-2} did not increase wheatgrass density without tillage. At that seeding rate, tillage increased wheatgrass tiller numbers 3-fold. Increasing seeding rate to 12,500 m^{-2} increased wheatgrass density over all other seeding rates. Plots tilled and seeded at 12,500 m^{-2} had the highest wheatgrass density (250 tillers m^{-2}) in 1996 at Hamilton.

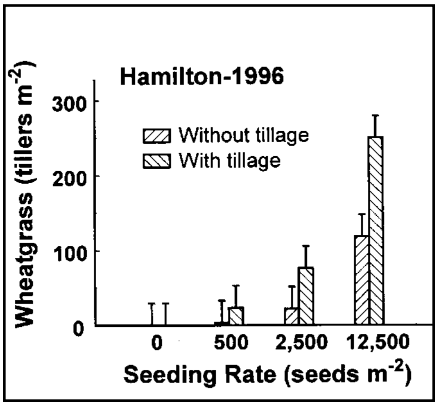

Fig. 1. Effect of tillage*seed rate on intermediate wheatgrass density at Hamilton in 1996. Error bars represent least significant differences ($\alpha = 0.05$).

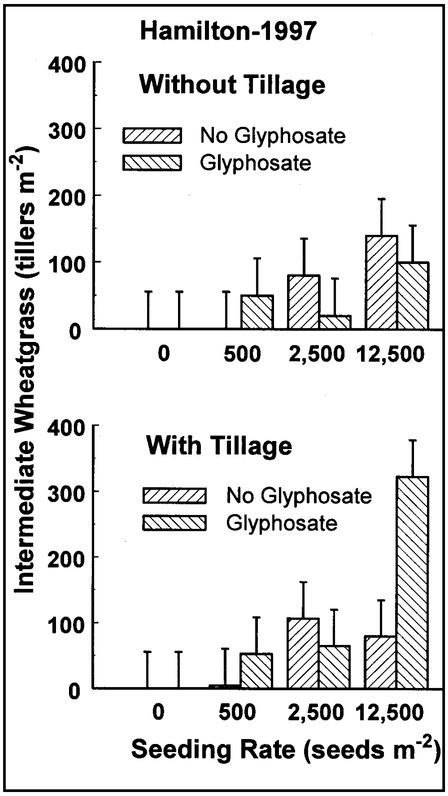

Fig. 2. Effect of tillage*glyphosate*seed rate on intermediate wheatgrass density at Hamilton in 1997. Error bars represent least significant differences ($\alpha = 0.05$).

By 1997, intermediate wheatgrass was not present in plots seeded at a rate of 500 m^{-2} when broadcast without tillage or glyphosate at Hamilton (Fig. 2). Increasing the seeding rate to 2,500 and 12,500 m^{-2} increased tiller density to about 80 and 140 m^{-2}, respectively. Neither tillage nor glyphosate increased wheatgrass tiller density, and glyphosate actually lowered tiller density when applied at the 2,500 m^{-2} seeding rate. At the highest seeding rate, combining tillage with glyphosate increased tiller density over 3 times more than other treatments where wheatgrass successfully established at Hamilton.

In 1996, only seeding rate affected intermediate wheatgrass biomass at Hamilton (Table 2). Seeding rates of 0, 500, 2,500, and 12,500 m^{-2} yielded 0.0, 0.3, 1.4, and 3.8 g m^{-2} ($LSD_{0.05}$ = 0.67) of biomass the first year after seeding. In 1997, seeding rate and tillage affected wheatgrass biomass at

Table 2. Pr ≤ F values generated from analysis of variance of density and biomass of intermediate wheatgrass, spotted knapweed and cheatgrass collected at Hamilton, Montana in 1996 and 1997.

Year	Treatment	df	Intermediate		Spotted knapweed		Cheatgrass	
			Density	Biomass	Density	Biomass	Density	Biomass
			(plants m^{-2})	(g m^{-2})	(plants m^{-2})	(g m^{-2})	(plants m^{-2})	(g m^{-2})
1996	Block	3	0.79	0.64	0.01	0.13	0.01	0.47
	Tillage	1	0.01	0.08	0.76	0.01	0.62	0.12
	Glyphosate	1	0.30	0.64	0.62	0.02	0.11	0.23
	Seeding rate	3	0.01	0.01	0.54	0.15	0.48	0.35
	Tillage*Glyphosate	1	0.05	0.11	0.90	0.35	0.23	0.47
	Tillage*Seeding rate	3	0.04	0.53	0.77	0.39	0.30	0.51
	Glyphosate*Seeding	3	0.47	0.11	0.82	0.67	0.53	0.45
	Till*Gly*Seeding rate	3	0.11	0.22	0.12	0.82	0.38	0.09
1997	Block	3	0.72	0.07	0.56	0.34	0.05	0.10
	Tillage	1	0.11	0.02	0.08	0.17	0.70	0.02
	Glyphosate	1	0.26	0.77	0.01	0.08	0.63	0.70
	Seeding rate	3	0.01	0.02	0.16	0.19	0.47	0.68
	Tillage*Glyphosate	1	0.08	0.31	0.19	0.75	0.57	0.42
	Tillage*Seeding rate	3	0.49	0.09	0.39	0.69	0.17	0.31
	Glyphosate*Seeding	3	0.05	0.43	0.29	0.27	0.77	0.31
	Till*Gly*Seeding rate	3	0.03	0.83	0.84	0.83	0.61	1.00

this site. Seeding rates of 0, 500, 2,500, and 12,500 m^{-2} yielded 0.0, 3.1, 3.8, and 4.0 g m^{-2}, ($LSD_{0.05}$ = 1.48), respectively indicating all nonzero seeding rates were similar 2 years after seeding. Tillage increased wheatgrass biomass from 1.56 to 3.85 g m^{-2} (P = 0.0242), regardless of seeding rate in 1997 at Hamilton.

Bozeman

In 1996, seeding rate*tillage and seeding rate*glyphosate interacted to affect intermediate wheatgrass tiller density at Bozeman (Table 3). Seeding at 500 or 2,500 m^{-2} without tillage did not increase wheatgrass tiller density over unseeded plots (Fig. 3a). Seeding at 12,500 m^{-2} increased wheatgrass density to about 64 tillers m^{-2}. As seeding rate increased, tillage increased wheatgrass density.

At Bozeman, seeding at 500 m^{-2} without glyphosate did not increase wheatgrass tiller density in 1996 (Fig. 3b). At that seeding rate, applying glyphosate increased wheatgrass density to 14 plants m^{-2}. Seeding at 2,500 m^{-2} produced about 22 tillers m^{-2}. Glyphosate had no effect on wheatgrass density at this seeding rate. Seeding rate of 12,500 m^{-2} without glyphosate increased wheatgrass density about 7 times those treatments with lower seeding rates. Application of glyphosate at this seeding rate nearly doubled wheatgrass density.

By 1997, only seeding rate determined the density of intermediate

Table 3. Pr ≤ F values generated from analysis of variance of density and biomass of intermediate wheatgrass, spotted knapweed and cheatgrass collected at Bozeman, Montana in 1996 and 1997.

Year	Treatment	df	Intermediate		Spotted knapweed		Cheatgrass	
			Density	Biomass	Density	Biomass	Density	Biomass
			(plants m^{-2})	(g m^{-2})	(plants m^{-2})	(g m^{-2})	(plants m^{-2})	(g m^{-2})
1996	Block	3	0.11	0.12	0.64	0.77	0.02	0.02
	Tillage	1	0.01	0.01	0.01	0.01	0.58	0.18
	Glyphosate	1	0.05	0.28	0.32	0.01	0.01	0.01
	Seeding rate	3	0.01	0.01	0.02	0.01	0.92	0.36
	Tillage*Glyphosate	1	0.10	0.11	0.90	0.35	0.23	0.47
	Tillage*Seeding rate	3	0.01	0.01	0.17	0.01	0.93	0.83
	Glyphosate*Seeding	3	0.02	0.59	0.24	0.14	0.95	0.54
	Till*Gly*Seeding rate	3	N/S	0.92	0.11	0.04	0.84	0.80
1997	Block	3	0.07	0.35	0.02	0.54	0.02	0.03
	Tillage	1	0.98	0.22	0.77	0.09	0.07	0.01
	Glyphosate	1	0.95	0.04	0.37	0.20	.017	0.57
	Seeding rate	3	0.01	0.01	0.13	0.32	0.65	0.68
	Tillage*Glyphosate	1	0.98	0.72	0.24	0.14	0.37	0.50
	Tillage*Seeding rate	3	0.91	0.03	0.89	0.64	0.63	0.98
	Glyphosate*Seeding	3	0.62	0.01	0.22	0.78	0.01	0.43
	Till*Gly*Seeding rate	3	0.90	1.00	0.98	0.68	0.60	0.80

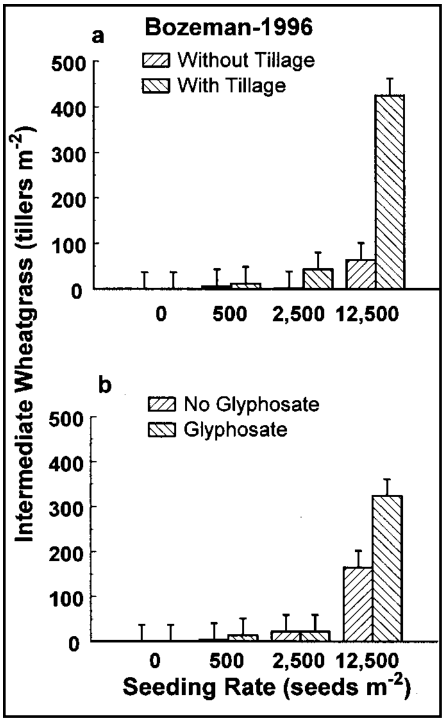

Fig. 3. Effect of tillage*seed rate (a) and glyphosate*seed rate (b) on wheatgrass density at Bozeman in 1996. Error bars represent least significant differences (α = 0.05).

wheatgrass tillers at Bozeman (Table 3). Increasing seeding rate from 0, 500, 2,500, and 12,500 m^{-2} increased wheatgrass density to 0.0, 67.3, 158.3, and 710.6 tillers m^{-2} respectively ($LSD_{0.05}$ = 87.0).

In 1996 and 1997, seeding rate*tillage interacted to affect intermediate wheatgrass biomass at Bozeman (Table 3). In 1996, the only treatment that increased the biomass of intermediate wheatgrass was the highest seeding rate combined with tillage (Fig. 4a). In 1997, seeding at a rate of 500 m^{-2} yield similar wheatgrass biomass as the unseeded plots (Fig. 4b). Wheatgrass biomass at this seeding rate was similar to that seeded with 2,500 m^{-2} and tilled. Seeding at 2,500 m^{-2} without tillage increased wheatgrass biomass over unseeded plots, but was similar to other treatments seeded with 500 or 2,500 seeds m^{-2}. Seeding with 12,500 m^{-2} without tilling doubled wheatgrass biomass over those plots seeded with 2,500 m^{-2} without tillage. Combining the highest seeding rate with tillage yielded the most wheatgrass biomass (28 g m^{-2}) of the seeding rate*tillage treatments in 1997.

Seeding rate also interacted with glyphosate to affect intermediate wheatgrass biomass in 1997 at Bozeman (Table 3). Of those plots seeded with 500 or 2,500 seeds m^{-2}, only those seeded at 2,500 combined with glyphosate yielded higher biomass than unseeded plots (Fig. 5). Seeding at 12,500 seeds m^{-2} without glyphosate yielded similar wheatgrass biomass as the latter treatment. However, combining the highest seeding rate with glyphosate yielded over 4 times the wheatgrass biomass of any other seeding rate*glyphosate treatment in 1997 at this site.

Spotted knapweed

Hamilton

In 1996, no treatment affected spotted knapweed density at Hamilton, but in 1997 glyphosate increased knapweed density from 305 to 419 plants m^{-2} ($P_{(0.05)}$ = 0.0068). However, tillage (P = 0.0015) and glyphosate (P = 0.0192) decreased knapweed biomass

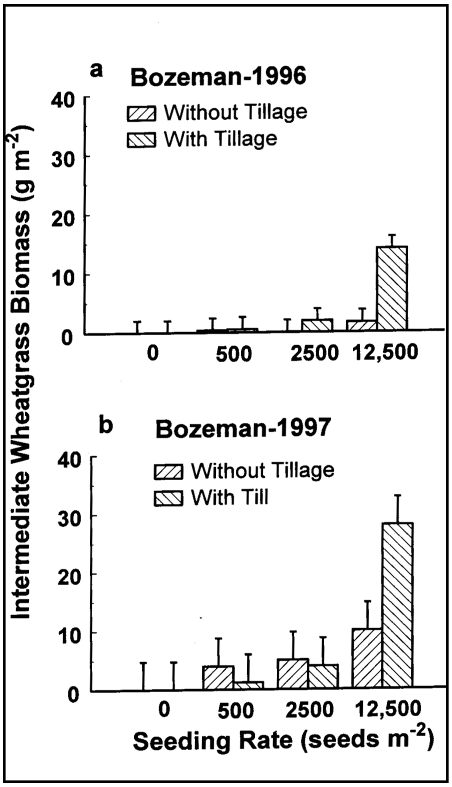

Fig. 4. Effect of tillage*seed rate on intermediate wheatgrass biomass at Bozeman in 1996 (a) and 1997 (b). Error bars represent least significant differences (α = 0.05).

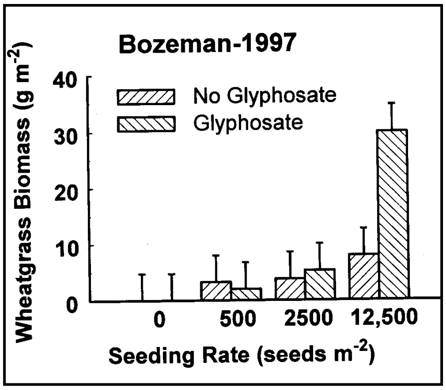

Fig. 5. Effect of glyphosate*seeding rate on intermediate wheatgrass biomass at Bozeman in 1997. Error bars represent least significant differences (α = 0.05).

from about 107 to 73 and 103 to 78 g m^{-2}, respectively, in 1996. By 1997, all treatment effects on spotted knapweed biomass were removed at Hamilton (Table 2).

Bozeman

In 1996, seeding rate (main effect) and tillage (main effect) affected spotted knapweed density (Table 3). Seeding rates of 0, 500, 2,500, and 12,500 m^{-2} produced 214, 208, 176, and 114 spotted knapweed plants m^{-2} ($LSD_{0.05}$ = 36.1) that year. At that time, tillage increased spotted knapweed density from 136 to 220 plants m^{-2} (P = 0.0008). By 1997, all treatment effects on spotted knapweed density were removed (Table 3).

In 1996, seeding rate, tillage, and glyphosate interacted to affect spotted knapweed biomass at Bozeman (Table 3). Without tillage or glyphosate, increasing seeding rate lowered spotted knapweed biomass (Fig. 6). Glyphosate lowered knapweed biomass in unseeded plots when applied without tillage. In plots without tillage those seeded and sprayed with glyphosate yielded lowest knapweed biomass. Tillage yielded similarly low spotted knapweed biomass, regardless of seeding rate or the application of glyphosate. However, by 1997 all treatment effects on spotted knapweed biomass were removed at Bozeman (Table 3).

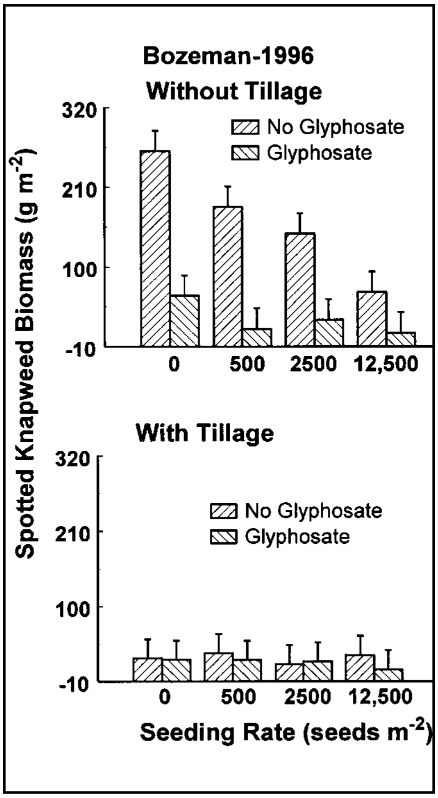

Fig. 6. Effect of tillage*glyphosate*seeding rate on spotted knapweed biomass at Bozeman in 1996. Error bars represent least significant differences (α = 0.05).

Cheatgrass

Hamilton

Tillage was the only treatment that affected cheatgrass at Hamilton (Table 2). Tillage increased cheatgrass biomass from 6.0 to 15.0 g m^{-2} (P = 0.0236) in 1997 at this site.

Bozeman

In 1996, glyphosate increased cheatgrass density from 54 to 126 (P = 0.0080) tillers m^{-2} at Bozeman. In 1997, seeding rate*glyphosate interacted to affect cheatgrass density (Table 3). At seeding rates of 0, 500, and 2,500 m^{-2} applying glyphosate decreased cheatgrass density, but at the 12,500 m^{-2} seeding rate glyphosate increased cheatgrass density at Bozeman (Fig. 7). In 1996, glyphosate increased cheatgrass biomass from 2.2 to 8.4 g m^{-2} (P = 0.0080) at Bozeman. Tillage increased cheatgrass biomass from 27.6 to 62.2 g m^{-2} (P = 0.0023) in 1997 at this site.

Discussion

Most revegetation studies of weed infested rangeland examine methods using agronomic seeding rates that are designed to optimize crop yield (Zimdall 1980). The recommended seeding rate of intermediate wheatgrass ranges from 170 (Granite Seed Co. Lehi, Utah) to 430 seeds m^{-2} (Sheley and Larson 1994). In this study, intermediate wheatgrass establishment did not occur at 500 seeds m^{-2} under any treatment or treatment combinations by the second growing season. This helps explain the high rate of failure in revegetating weed infested rangeland.

Our revegetation study suggests that increasing intermediate wheatgrass seeding rate will facilitate its establishment in spotted knapweed-cheatgrass infested rangeland. In many cases, increasing seeding rate increased intermediate wheatgrass density. We believe increasing the number of available seeds increased their probability of reaching safe sites (Harper et al. 1965, Wright et al. 1978).

In the first season after seeding, spotted knapweed density and biomass was reduced at high seeding rates at Bozeman. Establishment of intermediate wheatgrass may have reduced safe site availability for spotted knapweed, similar to that found by Larson and McInnis (1989) for yellow starthistle (*Centaurea solstitialis* L.). Weed competition may have been reduced at high wheatgrass densities (Jacobs et al. 1996, Velagala et al. 1997).

Tillage tended to enhance establishment of intermediate wheatgrass, especially at the highest seeding rate. Tillage may have created safe sites (Kocher and Stubbendieck 1986), while high seeding rates may have provided enough seeds to fill a majority of those safe sites (Young 1988, Call and Roundy 1991). In addition, improved soil conditions may have enhanced growth (Donahue et al. 1977). Although tillage prior to seeding can increase seedling establishment, many rangeland sites are unsuitable for tillage.

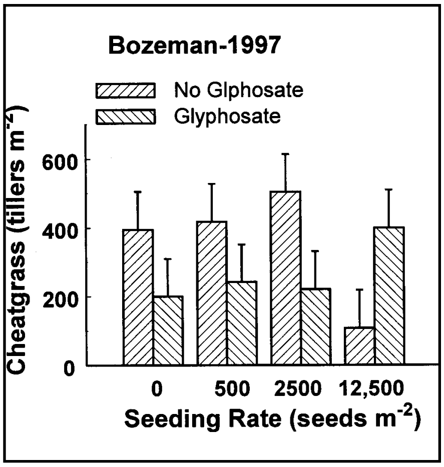

Fig. 7. Effect of tillage*seeding rate on cheatgrass density at Bozeman in 1997. Error bars represent least significant differences (α = 0.05).

Glyphosate increased spotted knapweed density, but reduced its biomass at Hamilton. In this case, we believe that the herbicide controlled a majority of mature spotted knapweed plants, but created safe sites available to knapweed, and in some cases, wheatgrass seedlings. Glyphosate reduced knapweed biomass when applied in conjunction with seeding at Bozeman. The effect of glyphosate on controlling cheatgrass was variable between sites and years. Variations in the effects of glyphosate may be dependant on weather and plant phenology (Dewey et al. 1997).

Implications for Management

It has been proposed that an appropriate goal for rangeland weed management would be to develop an ecologically-healthy plant community that is relatively weed-resistant, while meeting other land-use objectives (Sheley et al. 1996). Promoting or establishing competitive desirable grasses is essential for sustainable management of spotted knapweed. Land managers are reluctant to attempt revegetation because of the high costs and probability of failure. Our study showed that currently recommended seeding rates may account for the high failure of many rangeland seedings. We believe that revegetation success can be enhanced by increasing seeding rates.

It is generally accepted that herbicides are required to control weeds during the establishment of grasses. However, Velagala et al. (1997) indicated that weed competition only accounted for a small portion of the variation associated with seedling establishment in many situations, and density independent factors determine establishment success. Our study suggests that high seeding rates can help overcome the effect of weed competition and increase the probability of desirable seeds reaching safe sites. Using high seeding rates to control spotted knapweed and enhance seedling establishment may increase the effectiveness of broadcast seedings on steep or inaccessible rangeland, where many weed infestations exist. Although the seeding rates used in this study are extraordinarily high, strip or patch seeding may ensure seedling establishment, after which, natural dispersal may occur. In addition, this may allow the inclusion of broad leaved species that may contribute to the health of the plant community and increase its resistance to invasion (Tilman 1996).

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