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Herbicide Effects on Density and Biomass of Russian Knapweed (*Acroptilon repens*) and Associated Plant Species[1]

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Abstract: Sustainable invasive weed management must address treatment effects on desired vegetation. Our objective was to determine the influence of clopyralid plus 2,4-D, glyphosate, and fosamine, at various application rates and timing, on the density and biomass of Russian knapweed and desired plant groups growing in association with this invasive weed. In a randomized complete block design with four replications, three herbicides by three herbicide rates by three herbicide application timings and a nontreated control were factorially applied to two sites located along the Missouri River riparian corridor in Montana. Clopyralid plus 2,4-D, glyphosate, and fosamine were applied during the spring rosette stage of Russian knapweed (June), the bud to bloom stage of Russian knapweed (July), or the flowering stage of Russian knapweed (August). Herbicide rates were considered low, medium, and high based on label rates of clopyralid plus 2,4-D, glyphosate, or fosamine. Density and biomass of all species were sampled 3 yr after treatment. Russian knapweed biomass decreased from 125 to about 25 g/m^2 using clopyralid plus 2,4-D, irrespective of rate or timing of application. Russian knapweed density was reduced by about half by this mixture of herbicides. Nonnative grass density and biomass were maintained, whereas native grasses increased using clopyralid plus 2,4-D at medium or high rates. Neither glyphosate nor fosamine provided substantial Russian knapweed control or increases in grasses. Too few forbs were present to analyze their response to the treatments. We believe that herbicides must be combined with revegetation in areas lacking a diverse mixture of desired species capable of capturing resources made available by controlling Russian knapweed.

Nomenclature: Clopyralid; 2,4-D; fosamine; glyphosate; Russian knapweed, *Acroptilon repens* (L) DC. #[3] CENRE.

Additional index words: Native plants, restoration.

Abbreviation: SE, standard error.

INTRODUCTION

Nonnative invasive plants can reduce wildlife habitat and livestock forage (Hakim 1979; Lym and Messersmith 1987; Thompson 1996; Trammel and Butler 1995), increase soil erosion and stream sedimentation (Lacey et al. 1989), and decrease plant species diversity (Tyser and Key 1988). One such invasive species of concern is Russian knapweed, a rhizomatous perennial forb with spreading black roots, that is difficult to control and considered to be the most persistent of the knapweeds (Lacey 1989).

Russian knapweed is native to Eurasia and was introduced to North America in the early 1900s as a contaminant of Turkistan alfalfa (*Medicago sativa* L.) (Watson 1980). This invasive weed is widespread throughout the western United States and adjacent Canada, with severe infestations occurring in California, Idaho, Montana, Oregon, and Washington (Carpenter and Murray 1999). In Montana alone, Russian knapweed has infested approximately 26,000 ha (Duncan 2001) and is common on Missouri River bottomlands in the north-central part of the state (Zouhar 2001).

Infestations of Russian knapweed can displace desirable vegetation through a combination of competition and allelopathy (Maddox et al. 1985; Whitson 1999). As a result, reductions in forage production for wildlife and livestock can occur. Kurz et al. (1995) found that Russian knapweed caused a large shift in species composi-

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

tion for both plant and small-mammal communities, constituting a loss of forage, habitat, and overall rangeland biodiversity. Russian knapweed is generally avoided by grazing animals (Watson 1980). Fresh and dried plants are poisonous to horses and can cause a fatal neurological disorder called nigropallidal encephalomalacia (Panter 1991; Robles et al. 1997). Previous research indicates that Russian knapweed has decreased feed and market values of hay (Rogers 1928; Watson 1980). In addition, Russian knapweed has reduced grain yields 28 to 75% and fresh weight of corn yields 64 to 88% (Watson 1980) and has caused cropland to be abandoned (Maddox et al. 1985; Renny and Dent 1958).

It has become clear that controlling Russian knapweed is paramount to recovering and maintaining the plant communities that it infests. Previous attempts to control Russian knapweed have typically included an herbicide component. Herbicides alone can effectively suppress Russian knapweed infestations, but single applications are usually limited to short-term control (Bottoms and Whitson 1998). Fall applications of various herbicides provided 91 to 100% control of Russian knapweed 1 yr after treatments (Whitson et al. 1992). On Colorado rangeland, Sebastian and Beck (1993) applied numerous formulations of picloram, dicamba, chlorsulfuron, and metsulfuron, at different rates and timings to Russian knapweed. Picloram applied at 1.12 kg ai/ha in spring reduced Russian knapweed by 91% 2 yr after treatment; picloram applied at the same rate in the fall provided 86% control of Russian knapweed 3 yr after treatment. Duncan (1994) also found picloram to be the most effective herbicide for controlling Russian knapweed, regardless of application timing. However, picloram is highly mobile and can persist in soils for several years (Tu et al. 2001). Therefore, its use may be inappropriate in areas of ecological sensitivity or where water contamination is a concern. Herbicides with low environmental effect also have been tested for efficacy on Russian knapweed suppression. Benz et al. (1999) found that a July application of clopyralid plus 2,4-D reduced Russian knapweed cover 92% 2 yr after treatment.

Research suggests that integrating grass competition with herbicides can be more effective for providing long-term control of Russian knapweed than herbicides used alone (Bottoms and Whitson 1998). Whitson (1999) reported that 5 yr after initial treatments, the lowest amount of Russian knapweed (13.1%) and the highest percent live canopy of grasses (24.2%) were found in areas treated with clopyralid plus 2,4-D and seeded to streambank wheatgrass [*Elymus lanceolatus* (Scribn. & Smith) Gould]. However, clopyralid plus 2,4-D was reapplied 2 yr after initial treatments. In a different study, various grass species seeded after a clopyralid plus 2,4-D application produced 66 to 93% less Russian knapweed biomass than where no grass was sown (Benz et al. 1999).

Although seeding competitive grasses can be an important component for controlling Russian knapweed, revegetation is expensive and has a high risk of failure (Sheley et al. 2001). In areas with a substantial composition of desirable species, herbicides alone can remove the target weed and possibly shift the competitive balance in favor of the desirable plant community. However, previous research involving herbicide suppression of Russian knapweed has focused primarily on controlling the weed, with limited regard to the effects on the existing plant community. The effects of herbicide applications on native plant communities are poorly understood (except Rice et al. 1997). To achieve land-use objectives such as wildlife production, invasive weed management strategies must address the effects on desirable vegetation.

The overall objectives of this study were (1) to determine whether herbicides have the ability to increase density and biomass of existing desirable species, while controlling Russian knapweed and (2) to quantify the response of those residual species. Our specific objective was to determine the influence of clopyralid plus 2,4-D, glyphosate[4] (without surfactant), and fosamine, at different application rates and timings, on Russian knapweed and associated existing plant groups, based on species density and biomass. We hypothesized that clopyralid plus 2,4-D, applied at the highest rate during flowering, would provide the lowest density and biomass of Russian knapweed and desirable forbs and shrubs and the highest density and biomass of grasses. Although this study focused on the rehabilitation of a Russian knapweed–infested plant community, results of herbicide effects on existing plant species groups can be useful for determining appropriate management strategies in areas dominated by other invasive species.

MATERIALS AND METHODS

Study Sites. This study was conducted in north-central Montana on the Charles M. Russell National Wildlife Refuge, about 105 km north (22°29′N, 23°29′E) of Lewistown, MT. Two study sites were located on a floodplain

[4] Rodeo® formulation, Monsanto Company, 800 North Lindbergh Boulevard, St. Louis, MO 63167.

Table 1. Native and nonnative forbs and native shrubs located on the study sites.

Common name	Scientific name
Native forbs	
Western yarrow	*Achillea millefolium* L.
Povertyweed	*Iva axillaris* Pursh
American vetch	*Vicia americana* Muhl. ex Willd.
Nonnative forbs	
Whitetop	*Cardaria draba* (L.) Desv.
Field bindweed	*Convolvulus arvensis* L.
Small tumbleweed mustard	*Sisymbrium loeselii* L.
Flixweed tansymustard	*Descurainia sophia* (L). Webb ex Prantl
Alfalfa	*Medicago sativa* L.
Yellow sweetclover	*Melilotus officinalis* (L.) Lam.
Dandelion	*Taraxacum officinale* Weber
Yellow salsify	*Tragopogon dubius* Scop.
Field pennycress	*Thlaspi arvense* L.
Littlepod false flax	*Camelina microcarpa* DC.
Lambsquarters	*Chenopodium album* L.
Wild onion	*Allium ascalonicum* L.
Native shrubs	
Western snowberry	*Symphoricarpos occidentalis* Hook.
Silver sagebrush	*Artemisia cana* Pursh

known as Knox Bottom along the Missouri River, near the western boundary of the refuge. Sites were on a north aspect of 0 to 2% slopes at 670-m elevation with an annual average precipitation of 300 mm and an annual average temperature of 7 C. Soils at both sites were Kobar silty clay loams, which are fine, montmorillonitic Borollic Camborthids. These soils were formed in alluvium material and have slow permeability (USDA 1978).

Study sites were located within the silver sage–western wheatgrass (*Artemisia cana–Agropyron smithii*) habitat type (Hansen et al. 1995). Similar habitat types have been described for the northern Great Plains by Hanson and Whitman (1938), Mackie (1970), and Jorgensen (1979). This habitat type, common in central and eastern Montana, represents one of the driest extremes of the riparian zone. Plant communities at both sites consist of native and nonnative species, with few, but important, forbs (Table 1). The nonnative invader Russian knapweed was abundant at the study area and dominated the sites. Study sites were chosen based on similarities of habitat type as well as obvious differences in predominant graminoid species. Grass species at site 1 were dominated by quackgrass [*Elytrigia repens* (L.) Desv. ex Nevski], a nonnative grass, whereas the native western wheatgrass (*Pascopyrum smithii* P.A. Love) was the dominant grass species at site 2.

The silver sage–western wheatgrass habitat type typically occurs as a result of disturbance, where site potential has changed, possibly because of prolonged heavy grazing (Hansen et al. 1995). Land use at these sites from approximately the 1920s to the 1980s has included crop production and cattle grazing. Throughout that period, cattle were moved from upland summer pastures to the river bottoms for winter grazing. In addition, flooding from the Missouri River occurs with varying frequency and intensity. Because of its location within the Charles M. Russell National Wildlife Refuge, Knox Bottom provides critical wildlife habitat and continues to be managed for wildlife production.

Experimental Design. Twenty-eight treatments (three herbicides by three herbicide rates by three herbicide application timings, and a control) were factorially applied from June through August 2000 to 4.3- by 4.6-m plots in a randomized complete block design at both sites. Treatments were replicated four times at both sites for a total of 224 plots. Clopyralid plus 2,4-D, glyphosate, and fosamine were applied during the spring rosette stage of Russian knapweed (June), the bud to bloom stage of Russian knapweed (July), or the flowering stage of Russian knapweed (August) in accordance with Charles M. Russell National Wildlife Refuge and U.S. Fish and Wildlife Service restrictions. Low, medium, and high rates (clopyralid plus 2,4-D at 0.08 [clopyralid] + 0.42 [2,4-D], 0.13 + 0.67, and 0.18 + 0.92 kg ai/ha, respectively; glyphosate at 0.6, 1.2, and 1.8 kg ai/ha, respectively; fosamine at 3.6, 7.2, and 10.8 kg ai/ha, respectively) were applied based on label rates for Russian knapweed control. These herbicides were chosen because of their low environmental risk in areas near water and wildlife (Table 2). Herbicides were applied using a four-nozzle backpack sprayer delivering 130 L/ha of spray solution.

Sampling. Density was recorded for all existing plant species and Russian knapweed during June and August of 2001 and 2002. A Daubenmire frame (0.10 m^2) was randomly placed three times within each plot. Grasses were identified according to Cronquist et al. (1977), whereas forbs and shrubs were classified according to Dorn (1984). Biomass of all species was collected in August 2001 and 2002 using a 0.44-m^2 hoop randomly placed once within each plot. Plants were harvested at ground level and separated by species in the field. Plant material was then dried at 60 C for 48 h.

Data Analysis. ANOVA was used to determine the effects of site, year (after treatments), herbicide, application rate, and application timing on Russian knapweed and desirable plant species density and biomass. Treatment main effects and all interactions were included in the model. Five-way, four-way, and nonsignificant ($P >$

Table 2. Properties, soil and water behavior, and fish toxicity of herbicides (Vencill 2002).

Herbicide	Mode of action	Average soil half-life	Soil sorption K_{oc}	Soil mobility	Water solubility	LC_{50} (bluegill sunfish)
		d	ml/g		mg/L	mg/L
Clopyralid	Auxin mimic	40	Average 6	Moderate–High	1,000 (acid)	125 (moderate)
2,4-D	Auxin mimic	10	20 (acid)	Moderate–High	900 (acid)	263 (moderate)
Glyphosate	Inhibits the shikimic acid pathway, depleting aromatic amino acids	47	24,000	Low	900,000 (isopropyl-ammonium salt)	120 (moderate)
Fosamine	Mitotic inhibitor	8	150	Moderate	1,790,000	670 (low)

0.05) three-way interactions were pooled and included in the error term to improve the sensitivity of the analysis to detect lower order effects. Nonnative forb density data (+0.10; to adjust zero for transformation) were transformed to the $\log_{10}$ scale to meet homogeneity of variance and normality assumptions of ANOVA. Biomass data of nonnative forbs were square root transformed to meet ANOVA assumptions. When a significant P value ($P < 0.05$) was observed, mean separations for main effects and interactions were achieved based on standard errors (SE). Each SE was calculated by determining the square root of the quotient MSE/N, where MSE is the model mean square error and N is the number of experimental units associated with a main effect or interaction. Detecting mean differences with this SE calculation was appropriate because the number of experimental units (N) differed among treatments and controls, and it was necessary to incorporate varying sample sizes in the formula. For transformed data, untransformed means are presented with P values referring to transformed mean comparisons.

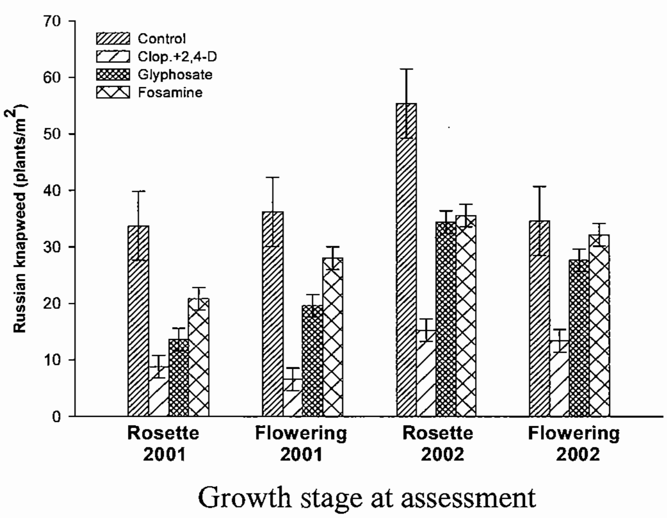

Figure 1. The effect of herbicide on Russian knapweed density at four sampling dates at two growth stages. Error bars represent standard error of 6.1 (controls) and 2.0 (treatments). Clop. = clopyralid.

Because of the infrequent occurrence of native forbs and native shrubs, no ANOVA models were appropriate for statistical analysis of these plant groups. Therefore, data related to native forbs and native shrubs were excluded.

RESULTS AND DISCUSSION

Russian Knapweed Density and Biomass. The effect of herbicides on Russian knapweed density was dependent on the growth stage at sampling and year after treatment ($P = 0.02$). For each herbicide, Russian knapweed density was lower than that of the control when sampled during the rosette stage in 2001 (Figure 1). The effect of fosamine on Russian knapweed density was no longer detectable by the flowering stage in 2001. Sampling during the rosette stage in 2002 indicated that glyphosate and fosamine produced similar Russian knapweed density as that of the nontreated control, which was 55 plants/m^2. Russian knapweed density was lowest in plots applied with clopyralid plus 2,4-D, regardless of growth stage at the time of sampling in 2002. Glyphosate or fosamine produced Russian knapweed densities similar to that of the control by the flowering stage in 2002. However, clopyralid plus 2,4-D reduced Russian knapweed density to less than half that of the control.

Russian knapweed density also was affected by an herbicide by rate by timing of application interaction ($P = 0.003$). Most rates of the three herbicides applied during the rosette growth stage reduced Russian knapweed density below that of the control (Figure 2). The one exception was that the low rate of fosamine did not affect Russian knapweed density. All herbicide and rate combinations applied at the bud and bloom stage reduced Russian knapweed density below that of the nontreated control. The medium and high rates of clopyralid

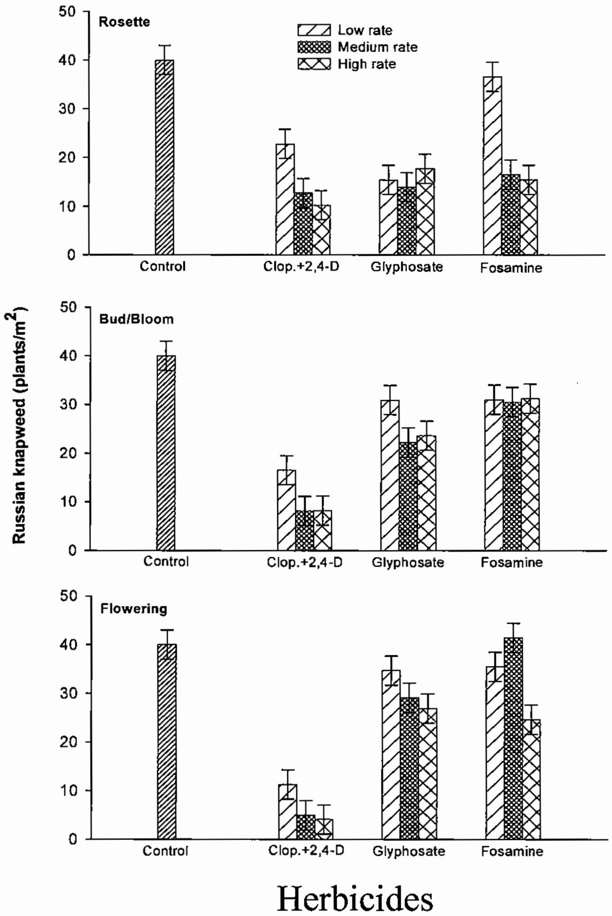

Figure 2. The effect of herbicide by application rate and timing on Russian knapweed density. Error bars for the controls and all treatments represent a standard error of 3.0. Clop. = clopyralid. Low, medium, and high rates are clopyralid plus 2,4-D at 0.08 (clopyralid) + 0.42 (2,4-D), 0.13 + 0.67, and 0.18 + 0.92 kg ai/ha, respectively; glyphosate at 0.6, 1.2, and 1.8 kg ai/ha, respectively; fosamine at 3.6, 7.2, and 10.8 kg ai/ha, respectively.

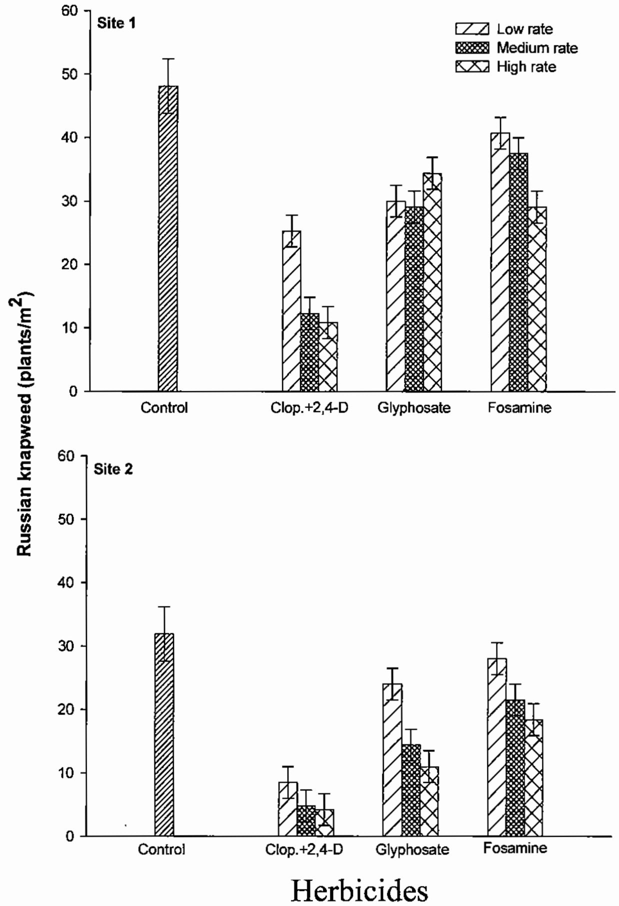

Figure 3. The effect of herbicide by application rate at sites 1 and 2. Error bars represent standard error of 4.3 (controls) and 2.5 (treatments). Clop. = clopyralid. Low, medium, and high rates are clopyralid plus 2,4-D at 0.08 (clopyralid) + 0.42 (2,4-D), 0.13 + 0.67, and 0.18 + 0.92 kg ai/ha, respectively; glyphosate at 0.6, 1.2, and 1.8 kg ai/ha, respectively; fosamine at 3.6, 7.2, and 10.8 kg ai/ha, respectively.

plus 2,4-D reduced Russian knapweed to about 8 plants/m². All three rates of clopyralid plus 2,4-D applied at flowering had the lowest Russian knapweed density, ranging from 4 to 11 plants/m².

ANOVA indicated that site, herbicide, and rate interacted ($P = 0.001$) to affect Russian knapweed density. Russian knapweed density was less than that of the control for all herbicide and rate combinations at site 1 (Figure 3). The clopyralid plus 2,4-D treatment provided the lowest control, averaging 16 knapweed plants/m² across the three rates, compared with 48 plants/m² in the control. There were about half as many Russian knapweed plants at medium or high rate of clopyralid plus 2,4-D than where this combination was applied at the low rate. Sites 1 and 2 had similar trends in Russian knapweed density, except that the low rate of fosamine did not affect Russian knapweed density at site 2. All other herbicides and rates decreased Russian knapweed density below that of the control. All three rates of clopyralid plus 2,4-D yielded the lowest Russian knapweed density, averaging 6 plants/m², whereas the control produced 32 plants/m². In contrast to site 1, there was no difference in Russian knapweed density among the three rates of clopyralid plus 2,4-D.

The effect of site on Russian knapweed density also was influenced by herbicide and application timing ($P = 0.004$). At site 1, the three application timings of clopyralid plus 2,4-D and the application of glyphosate at the rosette growth stage yielded the lowest Russian knapweed densities relative to the control (Figure 4). Among the clopyralid plus 2,4-D treatments, the reduction in knapweed density was about 13 plants/m² greater when applied during the bud–bloom and flowering period than the application on rosettes. Applying these herbicides during the rosette growth stage reduced Russian knapweed to about 24 plants/m², about half of those

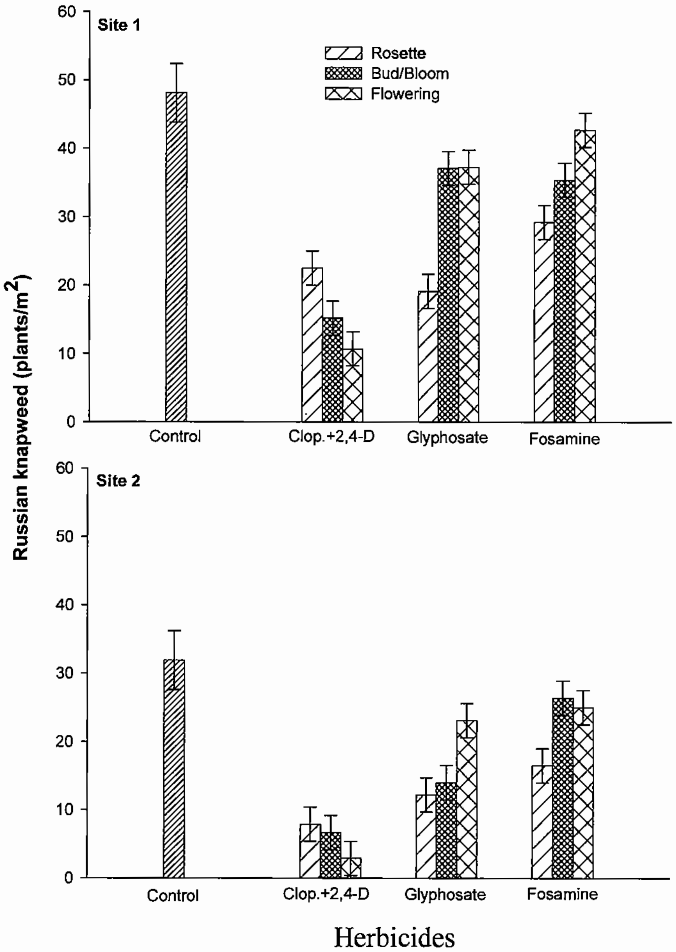

Figure 4. The effect of herbicide by application timing on Russian knapweed density at sites 1 and 2. Error bars represent standard error of 4.3 (controls) and 2.5 (treatments). Clop. = clopyralid.

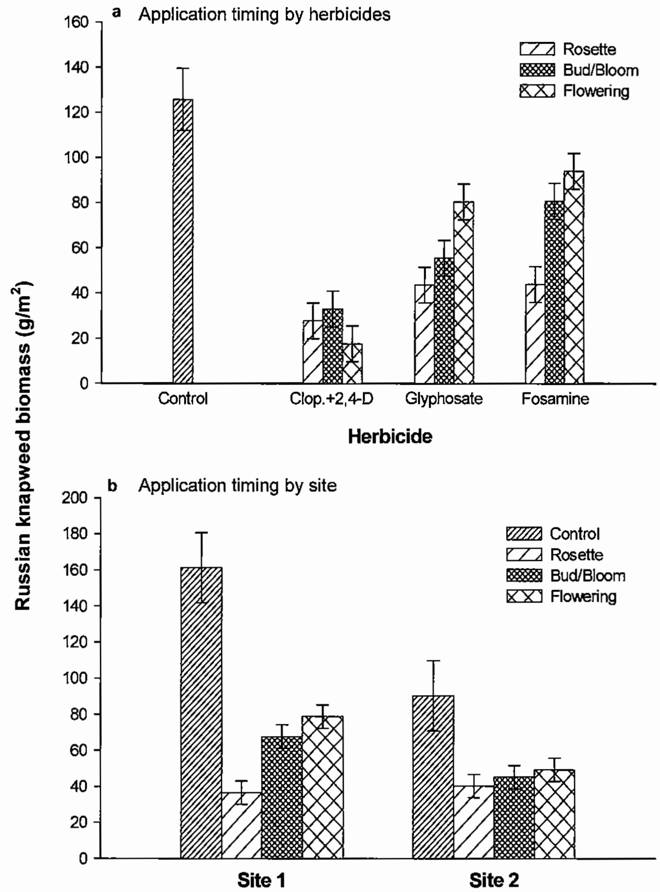

Figure 5. The effect of application timing by herbicide (a) and at sites 1 and 2 (b), on Russian knapweed biomass. Error bars in (a) represent standard error (SE) of 13.8 (control) and 7.9 (treatments). Error bars in (b) represent an SE of 19.4 (controls) and 6.5 (treatments). Clop. = clopyralid.

found in the nontreated control. At site 2, the lowest Russian knapweed density was associated with clopyralid plus 2,4-D, regardless of plant growth stage at the time of application. In addition, applications of glyphosate during either the rosette or the bud–bloom stages and the application of fosamine on rosettes all reduced knapweed density below 17 plants/m^2.

The effect of herbicides on Russian knapweed biomass depended on its growth stage ($P = 0.001$). All applications of the three herbicides reduced Russian knapweed biomass below that of the control (Figure 5a). Applications of clopyralid plus 2,4-D at any of the three growth stages provided similar Russian knapweed biomass, reducing it to an average of 26 g/m^2. Applications of glyphosate during the rosette or bud–bloom growth stages produced lower knapweed biomass than when applied during flowering. Fosamine applied to rosettes yielded about half as much Russian knapweed biomass as applying it during other growth stages.

There were differences in Russian knapweed biomass between sites based on the growth stage at the time of application ($P = 0.03$). At site 1, Russian knapweed biomass was reduced from 161 g/m^2 in the nontreated control to 37 g/m^2 when applied on rosettes across all herbicides (Figure 5b). However, there was no difference in Russian knapweed biomass among application timings. At site 2, the growth stage at the time of application did not influence Russian knapweed biomass. Application at any growth stage lowered biomass by about half that of the control.

Herbicides can provide effective short-term suppression of invasive weeds, including Russian knapweed (Bussan and Dyer 1999). Clopyralid (0.28 kg ai/ha) plus 2,4-D (1.49 kg ai/ha) provided 94% control of Russian knapweed in north-central Wyoming 2 yr after application (Whitson et al. 1991). In this study, clopyralid plus 2,4-D reduced Russian knapweed biomass from 125 to about 25 g/m^2 regardless of rate. Clopyralid plus 2,4-D also reduced Russian knapweed density by more than half 2 yr after treatment. We rejected our hypothesis that the highest rate of clopyralid plus 2,4-D would provide the best reduction of Russian knapweed density and biomass. In general, both medium and high rates of clopyralid plus 2,4-D provided the best Russian knapweed control.

The timing of herbicide application is important for weed control, and literature suggests that clopyralid plus 2,4-D is most effective for controlling Russian knapweed when applied from full bloom to the first killing frost (Bussan et al. 2001). In most cases, the effect of clopyralid plus 2,4-D on Russian knapweed biomass or density did not depend on its growth stage at application. Therefore, we rejected our hypothesis that application at flowering would provide the lowest density and biomass of Russian knapweed. The only exception was that application to rosettes reduced Russian knapweed biomass the most at site 1. Targeting Russian knapweed juveniles in spring can greatly reduce the productivity of an infestation and may minimize seed production. Whitson et al. (1991) found that applying clopyralid plus 2,4-D to Russian knapweed rosettes in May provided 76 to 81% control 1 yr after treatment.

Glyphosate reduced Russian knapweed density and biomass, but only temporarily because Russian knapweed density was equal to that of the control by August 2002. However, our data indicate that rosette and possibly bud–bloom applications of glyphosate appear to provide effective short-term suppression. Previous research showed that glyphosate applied at the bud stage and again to remaining live plants 2 mo later provided no Russian knapweed control 2 yr after treatment (Benz et al. 1999). Early spring applications of glyphosate can minimize effects on desirable species if applied before their emergence. However, we suspect that sequential glyphosate treatments during a growing season may reduce desirable species to levels at which they cannot effectively compete with Russian knapweed. Glyphosate[4] is labeled for use in and near water where Russian knapweed often grows, but it appears to lack the desired efficacy for Russian knapweed control (Bussan et al. 2001).

Fosamine is a selective herbicide that targets woody and herbaceous plants. However, the effects of fosamine vary and can be unreliable (Barring 1982). We found no published data that have examined the effects of fosamine on Russian knapweed. Based on this herbicide's low effect on aquatic systems and some success in controlling leafy spurge (*Euphoria esula* L.) (Tu et al. 2001), we wanted to determine whether fosamine could control

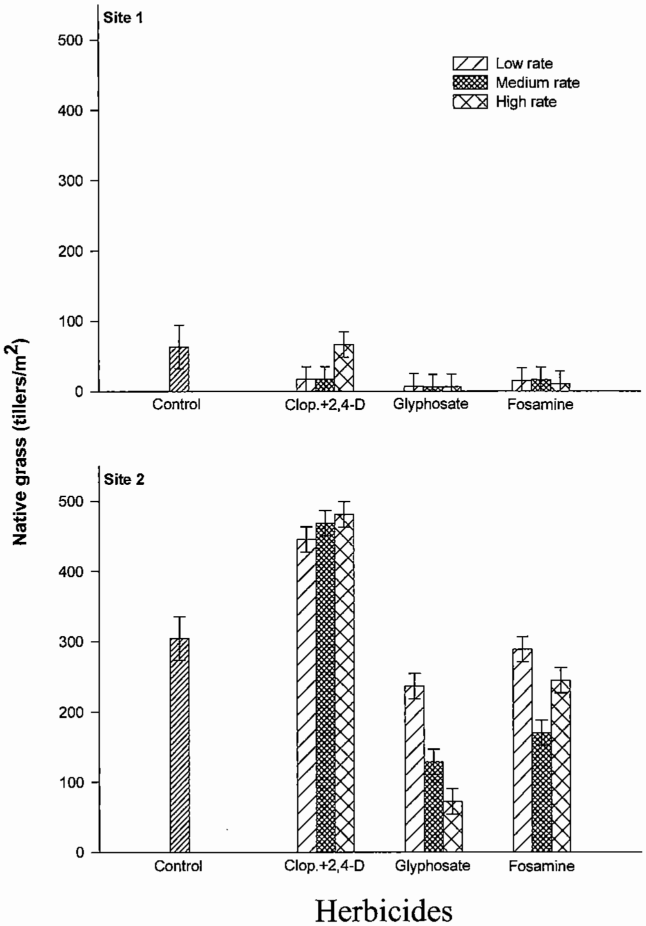

Figure 6. The effect of herbicide by application rate at sites 1 and 2 on native grass density. Error bars represent standard error of 31.2 (controls) and 18.0 (treatments). Clop. = clopyralid. Low, medium, and high rates are clopyralid plus 2,4-D at 0.08 (clopyralid) + 0.42 (2,4-D), 0.13 + 0.67, and 0.18 + 0.92 kg ai/ha, respectively; glyphosate at 0.6, 1.2, and 1.8 kg ai/ha, respectively; fosamine at 3.6, 7.2, and 10.8 kg ai/ha, respectively.

Russian knapweed in a riparian area. In general, fosamine treatments did not provide consistent control of Russian knapweed. However, higher rates applied to rosettes appear to have some potential for controlling Russian knapweed in riparian bottomlands. Because fosamine does not easily penetrate the leaves of mature plants (Hernandez et al. 1978), the efficacy of the June application may be attributed to the vulnerability of the juvenile Russian knapweed plants.

Grass Density and Biomass. The effect of herbicides on native grass density depended on the rate of application and site (P = 0.001). At site 1, all three rates of clopyralid plus 2,4-D had native grass tiller density similar to that of the control (Figure 6). Among clopyralid plus 2,4-D treatments, the high rate yielded the highest native grass density. All rates of glyphosate decreased native grass density below that of the control. The low

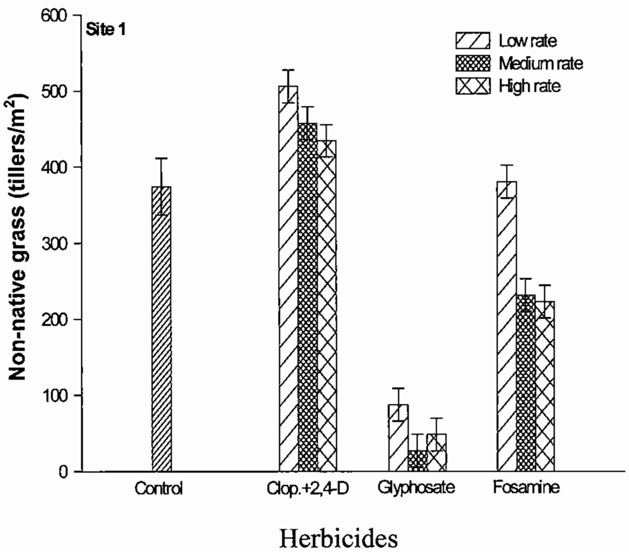

Figure 7. The effect of herbicide by application rate at site 1 on nonnative grass density. Error bars represent standard error of 37.3 (controls) and 21.5 (treatments). Clop. = clopyralid. Low, medium, and high rates are clopyralid plus 2,4-D at 0.08 (clopyralid) + 0.42 (2,4-D), 0.13 + 0.67, and 0.18 + 0.92 kg ai/ha, respectively; glyphosate at 0.6, 1.2, and 1.8 kg ai/ha, respectively; fosamine at 3.6, 7.2, and 10.8 kg ai/ha, respectively.

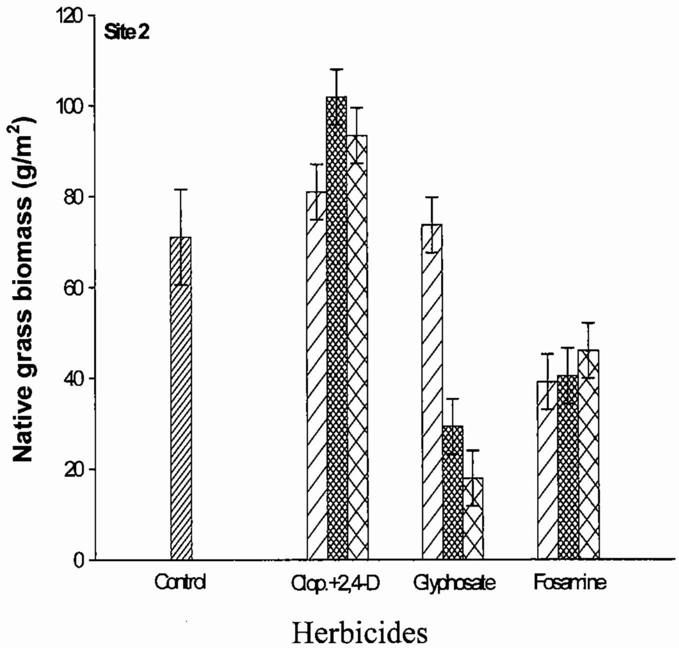

Figure 8. The effect of herbicide by application rate on native grass biomass at site 1. Error bars represent standard error of 10.5 (controls) and 6.1 (treatments). Clop. = clopyralid.

and medium rates of fosamine maintained native grass density relative to the control, whereas the high rate reduced grass density to about 11 tillers/m^2. At site 2, clopyralid plus 2,4-D increased native grass density across all rates more than that of the control. Across all rates, application of clopyralid plus 2,4-D averaged 465 native grass tillers/m^2, which was about 160 tillers/m^2 more than that found in the nontreated control. Glyphosate lowered native grass density below that of the control, regardless of rate at site 2. The low rate of fosamine had no effect on native grass density, but the medium and high rates of this herbicide reduced tillers below that of the control.

The effect of herbicides on nonnative grass density depended on the rate of application and site ($P = 0.02$). At site 1, clopyralid plus 2,4-D produced 92 tillers/m^2 more than the control, regardless of rate (Figure 7). All glyphosate[4] rates reduced nonnative grass density to less than 87 tillers/m^2. The lowest rate of fosamine did not affect nonnative grass density, but the medium and high rates decreased these grasses to an average of 228 tillers/m^2. At site 2, no rate of any herbicide affected nonnative grass density, and the control yielded 36 nonnative grass tillers/m^2 (data not presented). The only exception was that the medium rate of glyphosate[4] increased nonnative grass density to 105 tillers/m^2.

The effect of herbicides on native grass biomass depended on their rate and site ($P = 0.001$). At site 1, no treatment changed native grass biomass from that of the control, which yielded 5 g/m^2 (data not presented). At site 2, only the medium and high rates of clopyralid plus 2,4-D had greater native grass biomass (averaging 98 g/m^2) than the 71 g/m^2 produced in the control (Figure 8). Native grass biomass was unaffected by the low rates of clopyralid plus 2,4-D or glyphosate[4] at this site. Furthermore, native grass biomass was less than that of the control after applying the medium or high rates of glyphosate,[4] as well as for all rates of fosamine.

Herbicide effects on nonnative grass biomass were dependent on site and application timing ($P = 0.002$). At site 1, application of clopyralid plus 2,4-D increased nonnative grass biomass more than that of the control, regardless of growth stage at the time of application (Figure 9). In contrast, nonnative grass biomass was less than that of the control for all glyphosate[4] application timings. Similar to that of the clopyralid plus 2,4-D treatments, fosamine applied during the rosette growth stage of Russian knapweed or during flowering increased nonnative grass biomass. Application of fosamine during the bud–bloom period did not affect biomass of this plant group. At site 2, there were no differences between any treatment and the control. The only difference in nonnative biomass occurred between the application of clopyralid plus 2,4-D at bud–bloom, which yielded 2 g/m^2, and the rosette application of fosamine, which yielded 19 g/m^2.

Neither glyphosate[4] nor fosamine provided substantial

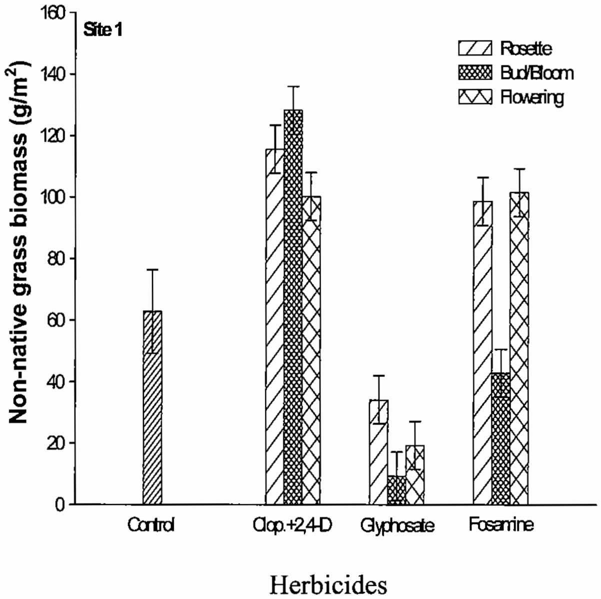

Figure 9. The effect of herbicide by application timing on nonnative grass biomass at site 1. Error bars represent standard error of 13.6 (controls) and 7.8 (treatments). Clop. = clopyralid.

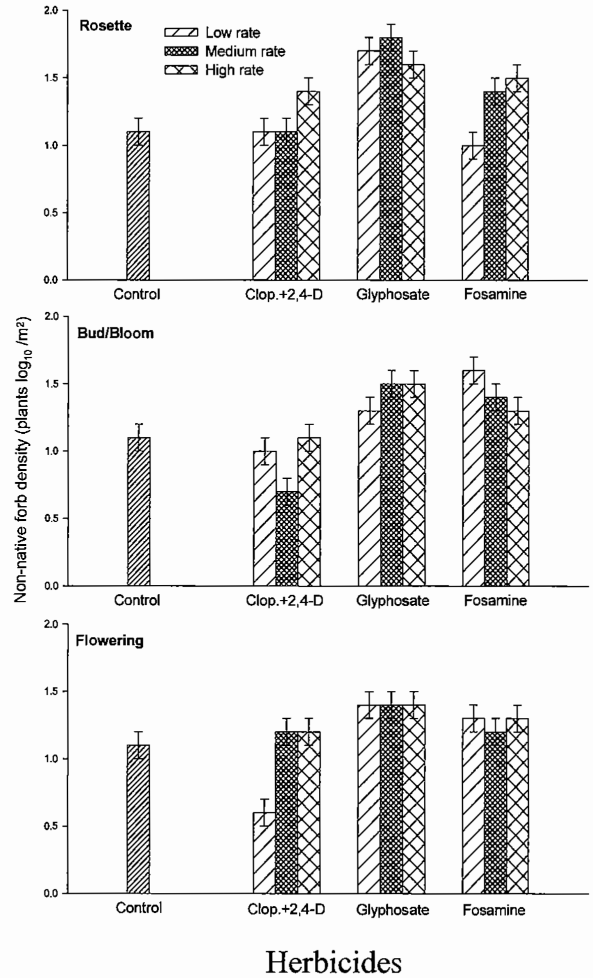

Figure 10. The effect of herbicide by application timing on nonnative forb density ($\log_{10} + 0.1$). Error bars represent standard error of 0.1 for controls and all treatments. Clop. = clopyralid. Low, medium, and high rates are clopyralid plus 2,4-D at 0.08 (clopyralid) + 0.42 (2,4-D), 0.13 + 0.67, and 0.18 + 0.92 kg ai/ha, respectively; glyphosate at 0.6, 1.2, and 1.8 kg ai/ha, respectively; fosamine at 3.6, 7.2, and 10.8 kg ai/ha, respectively.

Russian knapweed control or increases in grasses. However, application of clopyralid plus 2,4-D has increased grass abundance (Rice et al. 1997). Similarly, the medium and high rates of clopyralid plus 2,4-D increased native grass density and biomass on the site with a dominant residual understory of native grasses. Nonnative grasses were unaffected by clopyralid plus 2,4-D at this site. On the site codominated with nonnative grasses, clopyralid plus 2,4-D maintained native grass density and biomass regardless of rate, and nonnative grasses increased in density and biomass for all rates of clopyralid plus 2,4-D. The highest density and biomass of grasses did not result exclusively from the highest rate and application of clopyralid plus 2,4-D at flowering. The treatment effects on grasses appeared to be associated with the dominant grass composition at each site, i.e., native vs. nonnative grasses. We believe that the most abundant species capture the majority of resources, allowing them to usurp those resources faster than species occurring with less frequency.

Nonnative Forb Density and Biomass. The effect of herbicides on nonnative forb density depended on the rate and application timing ($P = 0.02$). Glyphosate increased nonnative forb density more than that of the control at all rates applied to rosettes (Figure 10). Effects of the other two herbicides varied according to application rates. Clopyralid plus 2,4-D applied on rosettes at low and medium rates maintained nonnative forb density. Native forb density increased to 54 plants/m² where this herbicide combination was applied at the high rate. The low rate of fosamine applied to Russian knapweed rosettes in June had no effect on nonnative forb density, whereas an increase in their density was detected for the medium and high rates. None of the rates of clopyralid plus 2,4-D applied at the bud–bloom growth stage increased nonnative forb density relative to the control. The medium rate of clopyralid plus 2,4-D reduced nonnative forb density to 37 plants/m², which was below that of the control. Where glyphosate[4] was applied during the bud–bloom stage, only the medium and high rates increased nonnative forb density. The low and medium rates of fosamine applied during the bud–bloom of Russian knapweed also yielded more nonnative forbs than the control. All glyphosate[4] rates applied at flowering increased nonnative forbs more than that of the

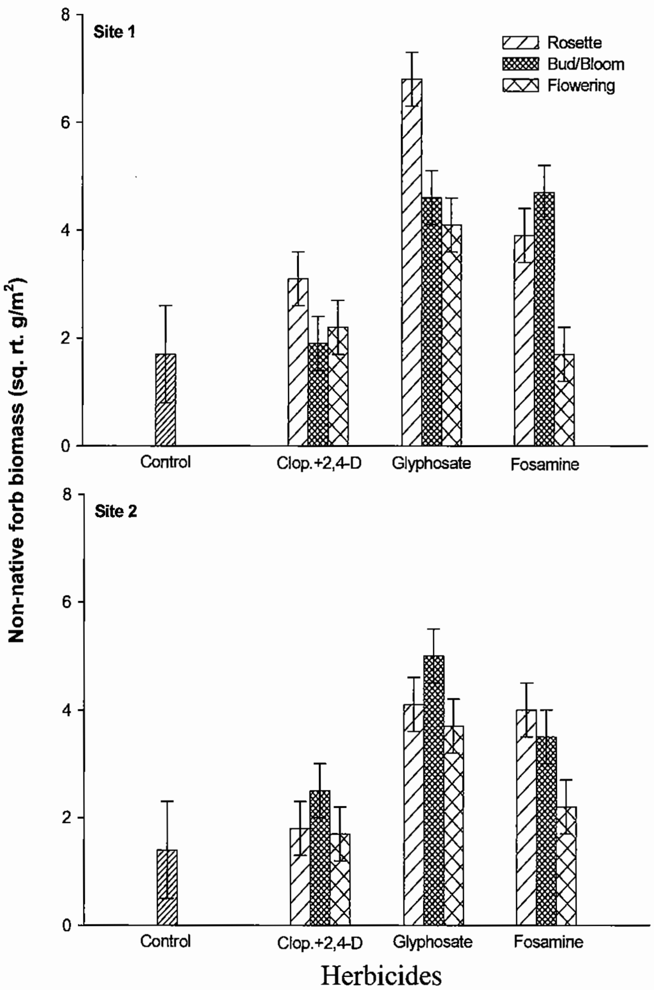

Figure 11. The effect of herbicide by application timing on nonnative forb biomass (square root g/m²) at sites 1 and 2. Error bars represent standard error of 0.9 (controls) and 0.5 (treatments). Clop. = clopyralid.

control. All rates of fosamine and the medium and high rates of clopyralid plus 2,4-D applied during flowering maintained nonnative forb density. The only treatment applied at flowering that produced a reduction in nonnative forb density relative to the control was the low rate of clopyralid plus 2,4-D, which produced 24 plants/m².

Herbicides' effect on nonnative forb biomass depended on timing of application and site (P = 0.04). No treatments at either site had nonnative forb biomass less than the control. At site 1, clopyralid plus 2,4-D applied at any time and fosamine applied at flowering did not influence nonnative forb biomass (Figure 11). All timings of glyphosate[4] increased nonnative forb biomass, which ranged from 26 to 69 g/m². Applications of fosamine applied to rosettes or during the bud–bloom growth stages increased nonnative forb biomass more than that of the control. Treatment effects at site 2 were similar to those at site 1.

Determining community-level effects from herbicides can be difficult when species frequency and abundance vary. Our native forb and shrub data could not be analyzed by ANOVA because of normality and homogeneity of variance violations. Marrs (1985) encountered similar difficulty because many species were not present in all the plots and occurred at low frequency where they did exist. By the inception of this study, we believe that Russian knapweed and other nonnative forbs had already reduced the native forb and shrub populations so much that they did not meet statistical requirements for ANOVA. We doubt any herbicide treatments could have facilitated a positive response because of the initial paucity of native forbs and shrubs.

Our study sites consisted of many nonnative forbs considered by land managers to be invasive species. Therefore, we were interested in treatments that reduced the density and biomass of this plant group. Rice et al. (1997) found that a June application of clopyralid plus 2,4-D caused a large reduction in nontarget forb cover. In our study, only the medium rate of clopyralid plus 2,4-D applied at bud–bloom and low rate applied at flowering decreased nonnative forb density. None of the treatments reduced nonnative forb biomass. Again, we rejected our hypothesis that the highest rate of clopyralid plus 2,4-D applied in August would provide the lowest density and biomass of nonnative forbs.

Of the herbicides tested in this study, clopyralid plus 2,4-D provided the best control of Russian knapweed. Although suppression 2 yr after treatments does not guarantee long-term control, we hoped to observe increases in the density and biomass of all desirable plant groups. These increases would have had the potential to direct the existing plant community on a positive trajectory toward meeting our wildlife production objectives. Because we detected increases only in grasses, we believe that the rehabilitation of the plant community's structure was not successful. Without sufficient community structure and competition from other critical plant groups, Russian knapweed will most likely recover from suppression treatments (Pokorny 2002).

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