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# Spotted knapweed, forb, and grass response to 2,4-D and N-fertilizer

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## Abstract

**Herbicidal control of spotted knapweed (*Centaurea maculosa* Lam.) on rangeland in the western United States has been most effective using residual herbicides, such as picloram (4-amino-3,5,6-trichloropicolinic acid). However, when residual herbicides cause concerns in riparian areas and for non-target forbs, management practices that use herbicides with lower soil persistence need to be developed. The objective of this study was to quantify the interaction between 2,4-D (2,4-Dichlorophenoxyacetic acid, dimethylamine salt) and N-fertilizer on spotted knapweed, other forbs, and grass density and biomass. Five 2,4-D rates (0.0, 0.6, 1.1, 1.6, and 2.2 kg ai ha$^{-1}$) and 5 N-fertilizer rates (0, 50, 100, 150, and 200 kg ha$^{-1}$) were applied to 2 spotted knapweed infested rangeland sites in a factorial combination arranged in a randomized-complete-block design during the summer of 1996 in Montana. Spotted knapweed, other forb, and grass density and biomass were measured at peak standing grass crop in 1997 and analyzed using analysis of variance. Spotted knapweed density and biomass at Rock Creek were reduced 50% and 65%, respectively, by 2,4-D of treatments of 1.1 kg ai ha$^{-1}$ or greater. Spotted knapweed biomass was slightly increased by N-fertilizer at 200 kg ha$^{-1}$. Grass density increased by about 50% when treated with 2,4-D of 1.1 kg ai ha$^{-1}$ or greater N-fertilizer did not affect grass density or biomass. At Hyalite Creek, 2,4-D at 0.6 kg ai ha$^{-1}$ reduced spotted knapweed density by 30%, and rates greater than 0.6 kg ai ha$^{-1}$ reduced it by 75%. Spotted knapweed biomass was reduced by 75% at all herbicide rates tested. N-fertilizer and 2,4-D interacted to increase grass density at Hyalite Creek; however, grass biomass was not affected. At Rock Creek, neither 2,4-D nor N-fertilizer affected forbs. At Hyalite Creek, 2,4-D and N-fertilizer interacted to increase aster (*Aster eatonii* [Gray] Howell) biomass. Death camas (*Zigadenus venenosus* Wats.) biomass was increased by N-fertilizer addition. Combining N-fertilizer with 2,4-D may increase long-term control of spotted knapweed when residual herbicides cannot be used. Application of 2,4-D at the bud stage of spotted knapweed growth will provide some control of spotted knapweed without affecting early season forbs.**

**Key Words: *Centaurea maculosa*, integrated weed management, maintaining plant diversity, herbicide/fertilizer interaction.**

## Resumen

**El control químico de "Spotted Knapweed" (*Centaurea maculosa* Lam.) en los pastizales del oeste de Estados Unidos ha sido más efectivo con herbicidas residuales como el picloram (ácido 4-amino-3,5,6-trichloropicolonico). Sin embargo, cuando los herbicidas residuales son una preocupación para las áreas ribereñas y las especies que no son el blanco del control, se deben desarrollar practicas que utilicen herbicidas con baja persistencia en el suelo. El objetivo de este estudio fue cuantificar la interacción entre el 2,4-D (ácido 2,4-Dichlorophenoxyacetico, sal de dimetilamina) y la fertilización nitrogenada sobre el "Spotted Knapweed", otras hierbas, y la densidad y biomasa de los pastos. Durante el verano de1996, se evaluaron cinco dosis de 2,4-D (0.0, 0.6, 1.1, 1.6 y 2.2 kg i.a. ha-1) y 5 dosis de fertilización nitrogenada (0, 50, 100, 150,y 200 kg ha$^{-1}$) en dos sitios de pastizal localizados en Montana e infestados de "Spotted Knapweed". El diseño experimental utilizado fue el de bloques completos al azar en un arreglo factorial. En 1997, cuando la producción de biomasa de los zacates estuvo en su pico máximo, se midió la biomasa y densidad de "spotted Knapweed", otras hierbas y pastos, los datos se analizaron mediante análisis de varianza. En el sitio de Rock Creek, los tratamientos de 2,4-D de 1.1 o más kg i.a. ha$^{-1}$, redujeron la densidad y biomasa de "Spotted knapweed" en 50% y 65% respectivamente. La biomasa de "Spotted knapweed" se incremento ligeramente con la fertilización nitrogenada de 200 kg ha$^{-1}$. La densidad de zacate se incrementó en aproximadamente 50% cuando el sitio se trato con 1.1 o más kg i.a. ha$^{-1}$ de 2,4-D. La fertilización nitrogenada no afecto ni la densidad ni la biomasa del pasto. En el sitio de Hyalite Creek, la dosis de 2,4-D de 0.6 o más kg i.a. ha$^{-1}$ redujo la densidad de "Spotted knapweed" en 30%, y dosis mayores de 0.6 kg i.a. ha$^{-1}$ la redujeron en 75%. La biomasa de "Spotted knapweed" se redujo en 75% con todos las dosis de herbicida evaluadas. En Hyalite Creek, la fertilización nitrogenada y el 2,4-D interactuaron para incrementar la densidad del pasto; sin embargo, la biomasa del pasto no fue afectada. En Rock Creek, ni el 2,4-D ni la fertilización nitrogenada afectaron las hierbas. En el sitio de Hyalite Creek, el 2,4-D y la fertilización nitrogenada interactuaron para incrementar la biomasa de "Aster" (*Aster eatonii* [Gray] Howell). La biomasa de "Death camas (*Zigadenus venenosus* Wats) se incremento con la adición de nitrógeno. Cuando herbicidas residuales no pueden ser utilizados, la combinación de fertilización nitrogenada con 2,4-D puede incrementar el control a largo plazo de "Spotted knapweed". La aplicación de 2,4-D en la etapa brotación del "spotted knapweed" proveerá algún control de esta especie sin afectar las hierbas que crecen a inicios de la estación**

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Spotted knapweed (*Centaurea maculosa* Lam.), an invasive Eurasian weed, has reduced forage production (Watson and Renney 1974, Spoon et al. 1983), increased soil erosion (Lacey et al. 1989), and lowered biodiversity (Tyser and Key 1989) on millions of hectares of rangeland throughout the western United States. This weed has spread to 356 counties in 15 western states and 2 Canadian Provinces during the past 100 years (Lacey et al. 1989, Sheley et al. 1998). The deeply taprooted perennial is an aggressive invader of rangeland dominated by Idaho fescue (*Festuca idahoensis* Elmer), rough fescue (*Festuca scabrella* Torrey ex Hook) and/or bluebunch wheatgrass (*Agropyron spicatum* (Prush) Scribn. & Smith). In Montana alone, where it is the most prevalent rangeland weed, spotted knapweed has infested about 2.2 million ha and has the potential to invade about 50% (20 million ha) of rangeland (Chicoine et al. 1985). Annual cost to the livestock industry in that state exceeds $11 million (Hersch and Leitch 1996).

Picloram (4-amino-3,5,6-trichloropicolinic acid) applied at a rate of 0.28 kg $ha^{-1}$ is most commonly used to control spotted knapweed on rangeland. Picloram residual of 12 to 30 months in the soil (Hamaker et al. 1967, Lacey 1985) and competition from residual perennial grasses (Hubbard 1975, Chicoine 1984, Sheley et al. 1984, Roché 1988) enables picloram to provide about 95% control of spotted knapweed for 2 to 5 years (Davis 1990). However, picloram is a restricted-use herbicide not available to most landowners with small ranchettes, and its use in riparian areas is prohibited because of its long persistence and high solubility.

Where picloram is unacceptable or a herbicide with lower persistence and solubility is preferred, the amine formulation of 2,4-D (2,4-Dichlorophenoxyacetic acid, dimethylamine salt) can provide an effective alternative. This herbicide, applied at 2.2 kg ai $ha^{-1}$, provides up to 90% control of spotted knapweed the year of application (Dewey et al. 1997). The optimum timing of 2,4-D application is during the active growing period of the target species. On level and accessible land, the cost associated with this treatment is about $25 $ha^{-1}$ (Lacey et al. 1997). On inaccessible areas, such as along rivers and streams, where 2,4-D is often the herbicide of choice, application costs can be as high as $125 $ha^{-1}$. For long-term control, 2,4-D must be applied annually until the soil seed bank has been depleted. Effective techniques that extend control using 2,4-D need to be developed for this herbicide to be cost effective. The expense associated with annual 2,4-D applications in inaccessible areas suggests that determining techniques which extend the longevity of control is necessary.

Integrating herbicides and fertilizers may have a synergistic effect on providing spotted knapweed control and enhancing grass yield and competitiveness. For example, Sheley and Roche (1982) found that combining picloram (0.28 kg $ha^{-1}$) with fertilizer (110 kg $ha^{-1}$; 16(N)-20(P)-0(K)) enhanced grass yield and competitiveness enough to minimize the reinvasion of spotted knapweed in northeastern Washington. More recently, Sheley and Jacobs (1997a) found that picloram plus fertilizer did not interact to affect either spotted knapweed or grass yield. However, fertilizer increased grass yield on the site where smooth bromegrass (*Bromus inermus* Leys.) and timothy (*Phleum pretense* L.) were the dominate grasses, but not on sites dominated by cheatgrass (*Bromus tectorum* L.) or Kentucky bluegrass (*Poa pratensis* L.). They speculated that increased grass yield would increase the duration of spotted knapweed control (Sheley and Jacobs 1997a).

The potential to use combinations of 2,4-D and fertilizer to manage spotted knapweed infested rangeland has not been investigated. Our objective was to quantify the effect of combining 2,4-D and N-fertilizer on spotted knapweed, grass, and other forb density and biomass. We hoped that a mid-summer application of 2,4-D would target spotted knapweed with minimum effect on early season forbs, and N-fertilizer would increase the competitiveness of grass thereby retarding the re-infestation of spotted knapweed. The theoretical basis for this hypothesis is that occupying more niches with a diversity of forbs and competitive grasses more efficiently uses limiting resources and reduces invasibility (Robinson et al. 1995).

## Materials and Methods

### Study Sites

Field studies were conducted during 1996 and 1997 on 2 sites in western Montana. Site 1 was within a *Festuca scabrella/Agropyron spicatum* habitat type (Mueggler and Stewart 1980) in the flood plain of Rock Creek, 32 km east of Missoula, Mont. (45° 53' 35"N,113° 59' 35"W) on an area previously under cultivation. The soil, a Bigarm gravely loam (loamy-skeletal, mixed, frigid, Typic Eutrochrepts) had 0 slope and an elevation of 1,160 m. Annual precipitation ranges from 406 to 457 mm and the frost-free period ranges from 70 to 90 days. Dominated by spotted knapweed, the site appeared to be in an advanced stage of invasion. Spotted knapweed density was high (140 plants $m^{-2}$, SD=52), the residual grass was suppressed, and there were few species of forbs. The suppressed grass understory consisted of scattered Kentucky bluegrass with small patches of smooth bromegrass. Other forbs consisted of low densities of yarrow (*Achillia millefolium* L.), sulfur cinquefoil (*Potentilla recta* L.), and silvery cinquefoil (*Potentilla argentea* L.).

Site 2 was on pasture land within the flood plain of Hyalite Creek 15 km west of Bozeman, Mont. (45° 36' 26"N, 111° 5'36"W). The area was within a *Festuca idahoensis/Agropyron spicatum* habitat type (Mueggler and Stewart 1980). The soil, a complex consisting of 70% Beaverton cobbly loam (loamy-skeletal over sandy or sandy-skeletal, mixed, Typic Argiborolls) and 30% Hyalite loam (fine-loamy, mixed, Typic Argiborolls) had 0 slope and an elevation of 1,340 m. Annual precipitation ranges from 381 to 483 mm and the frost-free period ranges from 90 to 110 days. This site appeared to be in the early stages of spotted knapweed invasion because it was dominated by Idaho fescue and native forbs with scattered spotted knapweed plants. Mean spotted knapweed density was 35 plants $m^{-2}$ (SD=11). Grass species present were Idaho fescue, bluebunch wheatgrass, Kentucky bluegrass, and smooth bromegrass. Other forbs that were present are listed in Table 1.

### Experimental Design

Twenty-five treatments (5 herbicide rates, 5 fertilizer rates) were applied to 2 m by 4 m plots and factorially arranged

**Table 1. List of forbs sampled at Site 2, Hyalite Creek**.

| Common name | Scientific name |
|---|---|
| Annual Forbs | |
| Large-flowered collomia | *Collomia grandiflora* Dougl. |
| Narrow-leafed collomia | *Collomia linearis* Nutt. |
| Indian lettuce | *Montia linearis* (Dougl.) Green |
| Shining chickweed | *Stellaria nitens* Nutt. |
| Perennial Forbs | |
| Yarrow | *Achillea millefolium* L. |
| Ballhead sandwort | *Arenaria congesta* Null. |
| Arnica | *Arnica longifolia* D.C. Eat. |
| Prairie sage | *Artemisia ludoviciana* Nutt. |
| Aster | *Aster eatonii* (Gray) Howell |
| Arrowleaf balsamroot | *Balsamorhiza sagittata* (Pursh) Nutt. |
| Larkspur | *Delphinium bicolor* Nutt. |
| Glacier lily | *Erythronium grandiflorum* Prush |
| Desert parsley | *Lomatium macrocarpa* (Nutt.) Coult.& Rose |
| Silvery lupine | *Lupinus argenteus* Pursh |
| Manyflowered phlox | *Phlox multiflora* A. Nels. |
| Smallflowered pennycress | *Thlaspi parviflorum* Nels. |
| Salsify | *Tragopogon dubious* Scop. |
| Death camas | *Zigadenus venenosus* Wats. |

in a randomized-complete-block design. The experiment was replicated 4 times at each site. In the summer of 1996, 2,4-D rates of 0.0, 0.1, 1.1, 1.6, and 2.2 kg ai ha$^{-1}$ were applied using a 4 nozzle backpack sprayer delivering 130 liter ha$^{-1}$ spray solution. A granular fertilizer, formulated as 32-0-0-0 (NPKS), was broadcast at rates of 0, 163, 326, 490, and 652 kg ha$^{-1}$ (0, 50, 100, 150, and 200 kg ha$^{-1}$ N) using a hand-cyclone applicator. The Rock Creek site was treated on 2 June 1996. Air temperature, soil temperature (surface), and relative humidity were 15.5°C, 21°C, and 78%, respectively, at the time of application. Winds were calm (<5 km hr$^{-1}$). The Hyalite Creek site was treated on 1 July 1996. Air temperature, soil temperature (surface), and relative humidity were 17.5°C, 21°C, and 50%, respectively at the time of application. Winds ranged from 0 to 6 km hr$^{-1}$. Spotted knapweed was in the bolt and bud growth stage at Rock Creek and Hyalite Creek, respectively, while other forbs were in various stages of senescence.

## Sampling

Density and biomass of spotted knapweed, grass and other forbs were sampled at peak standing crop (July) 1997. Densities were counted in a 0.1 m$^2$ (2 X 5 dm) frame (Daubenmire 1970) randomly placed within each plot. Grass species, Kentucky bluegrass and smooth bromegrass at Rock Creek and Idaho fescue, bluebunch wheatgrass, Kentucky bluegrass, and smooth bromegrass at Hyalite Creek, were counted by tiller. A 0.42 m$^2$ hoop was then placed to encircle the frame and biomass standing crop was harvested by species. Samples were dried at 60°C to constant weight and weighed.

## Data Analysis

Data were first analyzed with multiple linear regression (least squares) models using 2,4-D and N-fertilizer as independent variables. Scatterplots of the residual versus the standardized predicted values indicated that most of the data did not fit a linear model. Therefore, all data were analyzed using standard analysis of variance procedures. The 2 sites were analyzed separately because the original species compositions were different. The model included 2,4-D, N-fertilizer, and 2,4-D x N-fertilizer. When a significant ($P \leq 0.05$) F-test was observed, differences among means were tested using protected least significant differences (LSD) procedures (Peterson 1985). Forbs were analyzed as total forbs, total annual forbs, total perennial forbs, and by species.

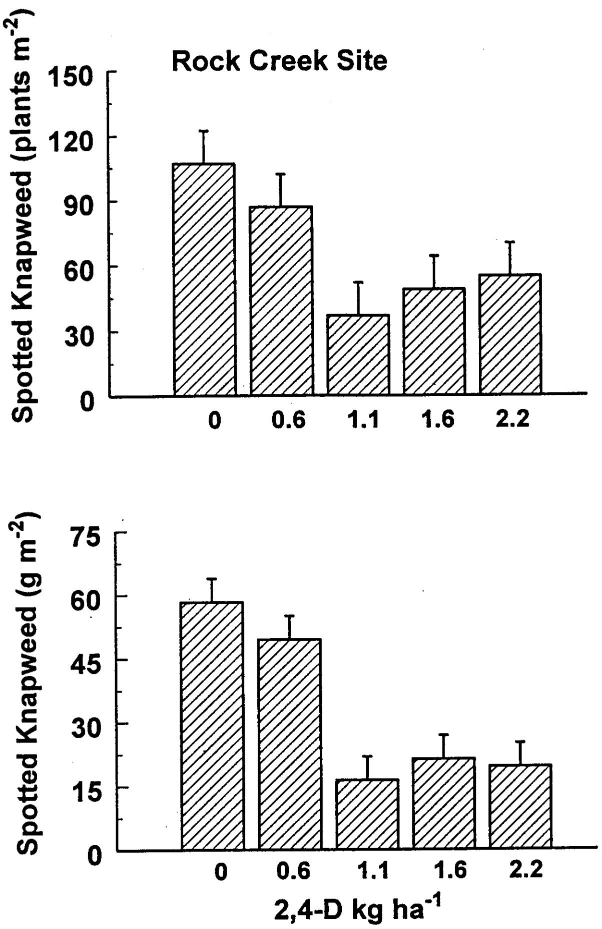


**Fig. 1. Effect of 2,4-D on spotted knapweed density (plants m$^{-2}$) and biomass (g m$^{-2}$) at Rock Creek. Error bars represent least significant differences (0.05).**

## Results

Two, 4-D and N-fertilizer did not interact to affect spotted knapweed density or biomass (Table 2, Table 3). On both sites, 2,4-D reduced spotted knapweed density and biomass the second season after treatment; however there were rate differences between sites. At Rock Creek, 2,4-D applied at 1.1 kg ai ha$^{-1}$ or greater reduced spotted knapweed density by about 50% and biomass by 65% (Fig.1). When 2,4-D was applied at 0.6 kg ai ha$^{-1}$ spotted knapweed density and biomass were similar to that of the control. At Hyalite Creek, spotted knapweed density was reduced by about 37% with 0.6 kg ai ha$^{-1}$ of 2,4-D (Fig. 2). Two,4-D applied at 1.1 kg ai ha$^{-1}$ and greater reduced spotted knapweed density by about 75%. All nonzero rates reduced spotted knapweed biomass by 75%. N-fertilizer did not affect spotted knapweed density or biomass at either site

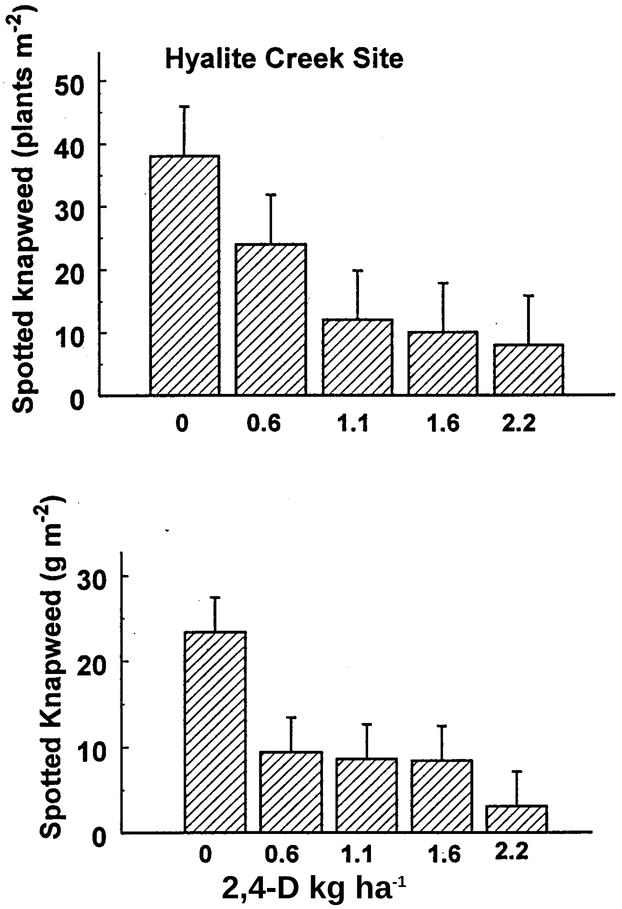


Fig. 2. Effect of 2,4-D on spotted knapweed density (plants $m^{-2}$) and biomass (g $m^{-2}$) at Hyalite Creek. Error bars represent least significant differences (0.05).

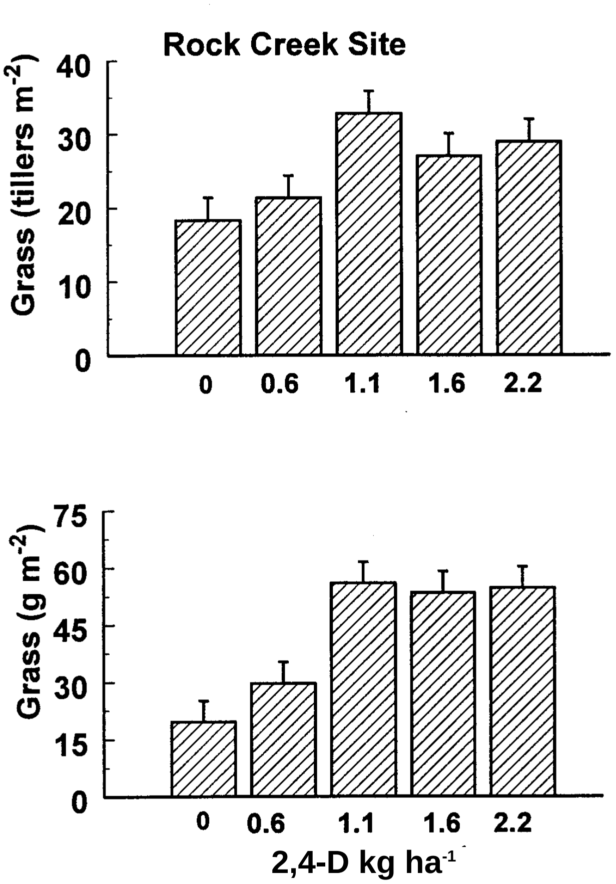


Fig. 3. Effect of 2,4-D on grass density (tillers $m^{-2}$) and biomass (g $m^{-2}$) at Rock Creek. Error bars represent least significant differences (0.05).

(Table 2, Table 3).

Combinations of 2,4-D and N-fertilizer did not interact to affect grass density or biomass at Rock Creek (Table 2). In addition, grass did not respond to N-fertilizer applications. Grass density and biomass did increase as a result of 2,4-D applications (Table 2, Fig. 3). Grass density increased slightly with 2,4-D applied at 1.1 kg ai $ha^{-1}$ or greater. Grass biomass increased 40% compared to the control when 2,4-D was applied at 0.6 kg ai $ha^{-1}$ and 65% compared to the control when 2,4-D was applied at 1.1 kg ai $ha^{-1}$ or more.

At Hyalite Creek, grass biomass was not affected by either 2,4-D or N-fertilizer, however, the combination interacted to increase grass density (Table 3). Grass density increased with 2,4-D application when no fertilizer was applied (Fig. 4). When no 2,4-D was applied, N-fertilizer did not increase grass density. When 2,4-D was applied at 1.1 kg ai $ha^{-1}$ or greater, adding 150 or 200 kg $ha^{-1}$ N-fertilizer caused an increase in grass density.

Forb density and biomass were unaffected by 2,4-D or N-fertilizer at Rock Creek (Table 2). At Hyalite Creek, forb density was also unaffected by 2,4-D or N-fertilizer, but treatments interacted to affect aster biomass and fertilizer increased death camas biomass (Table 3). Aster biomass was unaffected by 2,4-D or N-fertilizer when applied alone, however, when 200 kg $ha^{-1}$ of N-fertilizer was applied in combination with 2.2 kg ai $ha^{-1}$, aster biomass increased 10-fold (Fig. 5). Death camas biomass was increased about 3-fold by 50 kg $ha^{-1}$ N-fertilizer addition (Fig. 6).

Table 2. The significance probability associated with the F statistic (Pr≤F), generated from analysis of variance, for each species at the Rock Creek site.

| | Density | | | Biomass | | |
|---|---|---|---|---|---|---|
| Species | 2,4-D | N | 2,4-D*N | 2,4-D | N | 2,4-D*N |
| Knapweed | <0.01 | 0.98 | 0.63 | <0.01 | 0.07 | 0.29 |
| Grass | <0.01 | 0.64 | 0.76 | <0.01 | 0.57 | 0.99 |
| All Forbs | 0.62 | 0.23 | 0.89 | 0.55 | 0.35 | 0.83 |

## Discussion

It is becoming increasingly clear that the response of a

Table 3. **The significance probability associated with the F statistic (Pr≤F), generated from analysis of variance, for each species at the Hyalite Creek site.**

| | Density | | | Biomass | | |
|---|---|---|---|---|---|---|
| Species | 2,4-D | N | 2,4-D*N | 2,4-D | N | 2,4-D*N |
| Knapweed | <0.01 | 0.39 | 0.59 | 0.01 | 0.56 | 0.83 |
| Grass | <0.01 | <0.01 | 0.02 | 0.36 | 0.23 | 0.60 |
| All Forbs | 0.92 | 0.19 | 0.19 | 0.88 | 0.26 | 0.66 |
| Ann. Forbs | 0.55 | 0.27 | 0.19 | 0.58 | 0.31 | 0.47 |
| *Collomia* g. | 0.91 | 0.45 | 0.29 | 0.59 | 0.41 | 0.74 |
| *Collomia* l. | 0.50 | 0.15 | 0.17 | 0.51 | 0.99 | 0.32 |
| *Montia* | 0.40 | 0.13 | 0.19 | 0.78 | 0.41 | 0.44 |
| *Stellaria* | 0.78 | 0.71 | 0.53 | 0.63 | 0.77 | 0.58 |
| Per. Forbs | 0.89 | 0.88 | 0.49 | 0.46 | 0.60 | 0.87 |
| Yarrow | 0.64 | 0.76 | 0.18 | 0.47 | 0.79 | 0.57 |
| Sandwort | 0.62 | 0.72 | 0.23 | 0.39 | 0.81 | 0.38 |
| Arnica | 0.70 | 0.68 | 0.63 | 0.48 | 0.34 | 0.70 |
| Prairie sage | 0.65 | 0.84 | 0.56 | 0.61 | 0.84 | 0.54 |
| Aster | 0.91 | 0.26 | 0.63 | 0.02 | <0.01 | 0.03 |
| Balsamroot | 0.18 | 0.05 | 0.11 | 0.53 | 0.36 | 0.64 |
| Larkspur | 0.91 | 0.64 | 0.80 | 0.57 | 0.60 | 0.05 |
| Glacier lily | 0.06 | 0.47 | 0.14 | 0.27 | 0.18 | 0.47 |
| Desert parsley | 0.44 | 0.34 | 0.30 | 0.34 | 0.68 | 0.67 |
| Lupine | 0.65 | 0.37 | 0.70 | 0.27 | 0.46 | 0.67 |
| Phlox | 0.18 | 0.29 | 0.15 | 0.94 | 0.42 | 0.70 |
| Pennycress | 0.46 | 0.14 | 0.82 | 0.34 | 0.66 | 0.57 |
| Salsify | 0.42 | 0.53 | 0.28 | 0.56 | 0.61 | 0.55 |
| Camas | 0.67 | 0.93 | 0.96 | 0.61 | 0.04 | 0.10 |

plant community and the decision to use herbicides are dependent upon the composition and abundance of the residual species in the understory prior to application (Sheley et al. 1996, Sheley and Jacobs 1997a). As expected, the response of the plant community to 2,4-D and N-fertilizer combinations was dependent on the initial composition of the plant community. On the site dominated by spotted knapweed with a depleted grass and forb understory, only 2,4-D affected spotted knapweed, which resulted in a corresponding increase in grass density and biomass. At this site, we believe the release of grass from spotted knapweed suppression masked any effect the addition of N-fertilizer may have had. On the Idaho fescue-dominated site with a diverse forb component, 2,4-D and N-fertilizer interacted to increase grass density. Increasing grass density relative to spotted knapweed density has been shown to shift the competitive advantage from spotted knapweed to grass (Jacobs et al. 1996, Sheley and Jacobs 1997b).

The current recommended rate for controlling spotted knapweed using 2,4-D is 2.2 kg ai $ha^{-1}$ applied annually (Dewey et al. 1997). Our results show that 1.1 kg ai $ha^{-1}$ 2,4-D applied at bolt or bud stage had the same level of spotted knapweed control as higher rates the second season after treatment. N-fertilizer rates of 150 kg $ha^{-1}$ or greater increased grass density when 2,4-D was applied. These results suggest that 2,4-D applied at 1.1 kg ai $ha^{-1}$ applied in combination with 150 kg $ha^{-1}$ N-fertilizer should provide the optimum long-term control of spotted knapweed where persistent herbicides are not used.

Optimum rates of 2,4-D and/or 2,4-D plus N-fertilizer controlled spotted knapweed and increased grass yield without affecting other forbs. Plant diversity has been shown to improve plant community recovery from stress, such as drought (Tilman 1996) and increase resistance to plant invasion (Sheley et al. 1996, Tilman 1997). Jacobs and Sheley (1998a) found that northern sweetvetch (*Hedysarum boreale* Nutt.), a native, taprooted forb, when seeded with bluebunch wheatgrass reduced the competitiveness of spotted knapweed, supporting the theory that a diverse plant community is more resistant to weed invasion. Long-term control using repeated applications of picloram reduces forb diversity (Rice et al. 1997). Many native forbs that

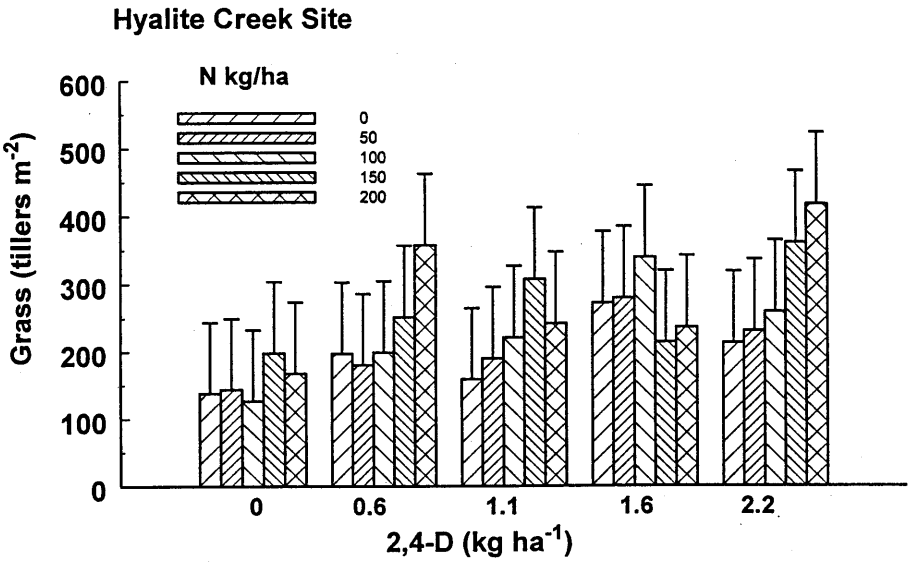


**Fig. 4. Effect of 2,4-D and N-fertilizer combinations on grass density (tillers $m^{-2}$) at Hyalite Creek. Error bars represent least significant differences (0.05).**

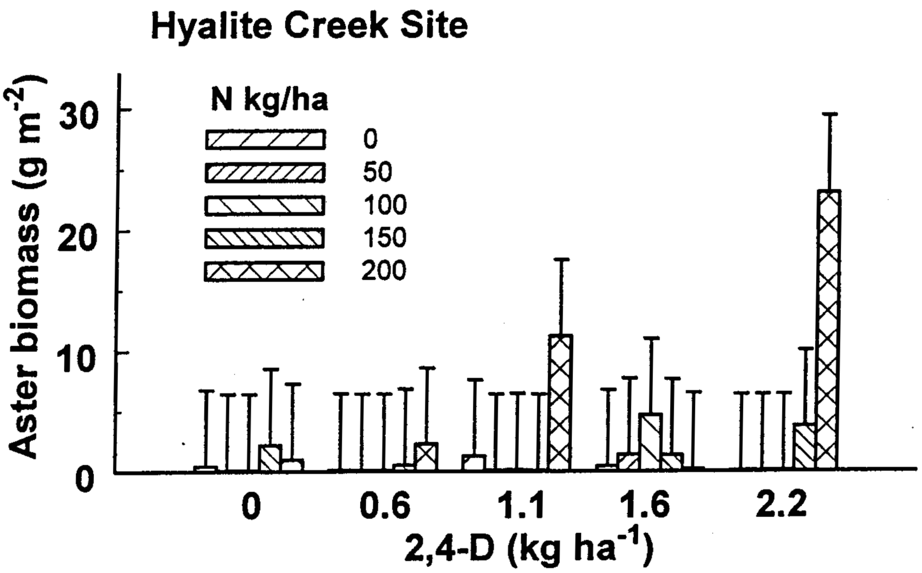


**Fig. 5. Effect of 2,4-D and N-fertilizer combinations on aster biomass (g $m^{-2}$), at Hyalite Creek. Error bars represent least significant differences (0.05).**

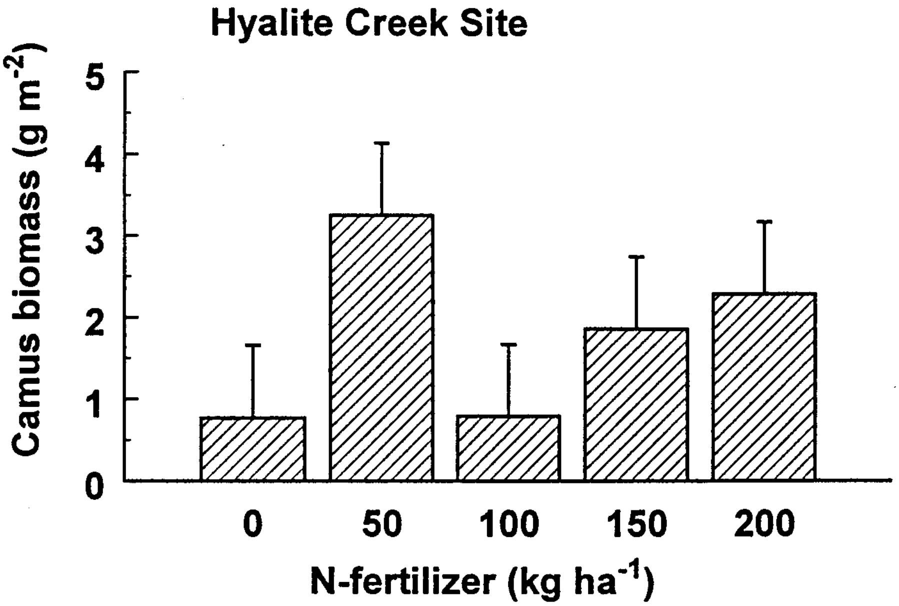


**Fig. 6. Effect of N-fertilizer on death camas biomass (g $m^{-2}$), at Hyalite Creek. Error bars represent least significant differences (0.05).**

emerge and mature early in the growing season are affected by picloram residue. Spotted knapweed remains actively growing throughout much of the summer (Jacobs and Sheley 1998b) and can be controlled with non-residual herbicide application at the bud stage of growth without affecting spring and early summer forbs. We believe that this creates a phenological and temporal opportunity to maximize herbicidal effects on spotted knapweed, while minimizing exposure to desirable native forbs. Furthermore, the lack of soil persistence of 2,4-D should limit long-term effects. Our study suggests that in areas with substantial residual native plant communities, 2,4-D plus N-fertilizer applied in mid-summer can effectively control spotted knapweed, and increase grass density over that of 2,4-D alone without reducing native forbs.

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