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# Meadow Knapweed (*Centaurea debeauxii*) Response to Herbicides and Mechanical Control

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Meadow knapweed is a fertile European hybrid between black and brown knapweed that has expanded its North American distribution to 27 of the United States and four provinces in Canada. Two experiments were conducted on meadow knapweed in northwestern Washington to determine (1) whether meadow knapweed is similarly sensitive to several herbicides commonly used to control related knapweeds, (2) if herbicide application timing plays a role in control of meadow knapweed, and (3) whether mowing before, after, or instead of herbicide treatment can aid in meadow knapweed control. In the first experiment, herbicides were applied to meadow knapweed at rosette or bolting stages of growth, and again with the same herbicides in the autumn. In the summer following treatment, clopyralid alone or with 2,4-D, dicamba + 2,4-D, and triclopyr ester + 2,4-D ester provided 81 to 100% meadow knapweed control; the only other treatment providing similar control was glyphosate + ammonium sulfate applied at bolting and in autumn in the 2004 to 2005 trial. In the second experiment, combinations of mowing and dicamba + 2,4-D were applied at rosette or early flowering stages of growth. In the 2002 to 2003 trial, control when dicamba + 2,4-D was used exceeded 90%, except when meadow knapweed was mowed at rosette and sprayed at early flowering (78% control). Mowing twice the previous year had only a slight effect on meadow knapweed (10% control). Grass biomass exceeded meadow knapweed biomass in all herbicide-treated plots. In the 2004 to 2005 trial, meadow knapweed control and grass biomass was maximized when plots were mowed at rosette and treated with dicamba + 2,4-D at early flowering or when treated twice with these herbicides; these were the only treatments where grass biomass exceeded meadow knapweed biomass.

**Nomenclature:** Clopyralid; dicamba; glyphosate; imazapic; MCPP; triclopyr; 2,4-D; meadow knapweed; *Centaurea debeauxii* Gren. & Godr. CEDE5.

**Key words:** Integrated weed management, invasive species, mowing.

Meadow knapweed (*Centaurea debeauxii* Gren. & Godr.) is a nonrhizomatous perennial in the plant family Asteraceae. It is a fertile hybrid between black knapweed (*C. nigra* L.) and brown knapweed (*C. jacea* L.) that reproduces by seed (Roché et al. 2003). The taxonomy of this species is complicated, with New York Flora Atlas (Weldy and Weirier 2013) noting that ''the *C. jacea* complex which is European in origin is a difficult group due to hybridization, polyploidy, apomixis, and morphological variation''. Since the nomenclature of meadow knapweed has been a source of confusion and will no doubt continue to be refined, readers are encouraged to consider the following composite description (from Anonymous 1995; Roché and Roché 1991; and Roché et al. 2003) for the weeds tested in these trials. Meadow knapweed stems are herbaceous, borne from a perennial semi-woody crown, ranging from 50 to 100 cm (20 to 40 in) tall. Basal leaves are often up to 15 cm long to 3 cm wide, tapering at both ends, and are variable in their level of lobing. Stem leaves are lanceolate, sessile, sometimes shallowly lobed, and are progressively smaller and less lobed near the inflorescence. Flowers are purple to rose (white) and borne in solitary, oval to globose heads at the branch tips. Heads are up to 20 mm (0.8 in) wide and are usually wider at the throat and less urn-shaped than heads of most other knapweed species currently introduced into western North America. Involucral bract tips are light to dark brown, about 3 mm wide and variably rounded with torn, thin, papery margins or bearing comb-like, fringed margins; these margins are about as wide as the bract itself. Flower heads are typically produced from July through September in the Pacific Northwest (PNW) and produce ivory-white to light brown

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## Management Implications

Meadow knapweed is a nonrhizomatous perennial hybrid of black and brown knapweed in the plant family Asteraceae that has been introduced from Europe into many of the United States and Canadian provinces. It is not as widespread in North America as certain other *Centaurea* species, so herbicides have not been widely tested for efficacy on this hybrid. Therefore, two experiments were conducted to determine (1) whether meadow knapweed is similarly sensitive to several herbicides commonly used to control related knapweeds, (2) if herbicide application timing plays a role in control of meadow knapweed, and (3) whether mowing before, after, or instead of herbicide treatment can aid in meadow knapweed control. Herbicides were applied either in spring + autumn or in summer + autumn in the first experiment; in the second experiment, dicamba + 2,4-D was applied either before or after mowing and compared to one or two herbicide applications or two mowings. In the first experiment, clopyralid alone or in combination with other herbicides provided up to 100% control of meadow knapweed in the year following treatments. Triclopyr, dicamba, and glyphosate also resulted in control. These herbicides are often used at similar rates and timings to achieve control of other *Centaurea* species, which indicates that meadow knapweed is as susceptible to these products as other knapweeds. In the second experiment, combinations of mowing and herbicide applications at rosette or early flowering stages of growth generally reduced meadow knapweed biomass and increased grass biomass, although herbicide treatment alone achieved the same result. Mowing twice was an ineffective control strategy for this knapweed hybrid. Therefore, mowing is not recommended to augment control of meadow knapweed when using herbicides.

achenes that sometimes bear a pappus at the apex. Roché et al. (2003) caution that black and brown knapweed and their resulting hybrids are tetraploid species bearing 44 chromosomes, so backcrosses are common and give rise to individuals that may closely resemble either parent or combine characters randomly.

Roché et al. (2003) report that meadow knapweed has expanded its range exponentially over the last several decades, and that it is now found in approximately 27 of the United States and four Canadian provinces, ranging from the Atlantic to the Pacific and as far south as North Carolina (USDA, NRCS 2013). The weed occurs in 53 of 119 counties in the three states of the PNW (USDA, NRCS 2013), infesting an estimated 9000 acres in Washington alone (Anonymous 1995).

Results of management efforts against this hybrid have not been frequently reported. Recommendations for chemical control of meadow knapweed in the PNW are frequently generic for all knapweed species and focus on auxinic herbicides (Prather et al. 2013). Four biological control insects have been approved for use on meadow knapweed in the United States, including the seedhead weevils *Larinus minutus* Gyllenhal (Coleoptera: Curculionidae) and *L. obtusus* Gyllenhal (Coleoptera: Curculionidae), the seedhead gall fly *Urophora quadrifasciata* Meigen (Diptera: Tephrididae), and the seedhead moth *Metzneria paucipunctella* Zeller (Lepidoptera: Gelechiidae) (Coombs et al. 2004; Roché et al. 2003). Control of meadow knapweed by these insects in the PNW has been rated as fair to good (Andreas et al. 2013) although data regarding successful reductions in meadow knapweed infestations from biocontrol agent release are lacking.

Reports of meadow knapweed control using mowing or livestock grazing are lacking, although there is evidence that density and seed production of other *Centaurea* species can be reduced by these means. Spotted knapweed (*C. stoebe* L.) cover and seedhead production were reduced when plants were grazed by goats at rosette and bloom stages of growth (Williams and Prather 2006), while sequential grazing by cattle followed by sheep beginning at the late-bud/early flower stage of growth has been recommended for spotted knapweed control (Henderson et al. 2012). Yellow starthistle (*C. solstitialis* L.) size and seed production were reduced by grazing bud stage plants prior to spine hardening (Thomsen et al. 1993), while seed production was reduced 93% when up to three mowings were augmented with subterranean clover (*Trifolium subterraneum* L.) planting (Thomsen et al. 1997). Yellow starthistle growth form also plays a role in successful control by mowing, as Benefield and co-workers (1999) found that erect yellow starthistle plants were nearly eliminated when mowing was conducted at the early flowering stage of growth, although low-growing plants were not adequately controlled even from multiple mowings.

Complaints to the authors from Clallam County, Washington landowners unhappy with performance of herbicides applied to meadow knapweed indicated that perhaps this *Centaurea* hybrid was responding differently to chemical control than other knapweeds. Therefore, an experiment was designed to evaluate the efficacy of several herbicides applied at different timings specifically on meadow knapweed. Because mowing and/or grazing prior to herbicide application has been shown to aid in control of common reed (*Phragmites australis* (Cav.) Trin. ex Steud.) (Derr 2008; Monteiro et al. 1999), spotted knapweed (Brown et al. 1999; Rinella et al. 2001), perennial pepperweed (*Lepidium latifolium* L.) (Renz and DiTomaso 2006), tropical soda apple (*Solanum viarum* Dunal) (Mislevy 1999), and wild chervil (*Anthriscus sylvestris* (L.) Hoffman) (Miller and D'Auria 2011), a second experiment was conducted concurrently to determine whether mowing prior to or following herbicide application would improve herbicide efficacy.

### Materials and Methods

The two experiments were conducted in non-irrigated pastures near Port Angeles and Quilcene, WA, both heavily infested with meadow knapweed. The herbicide experiment



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was conducted in 2001 to 2002 (Port Angeles) and repeated in 2004 to 2005 (Quilcene), while the herbicide/mechanical control experiment was conducted in 2002 to 2003 (Port Angeles) and repeated in 2004 to 2005 (Quilcene). The soil type for the Port Angeles trials was a Puget silt loam (Fine-silty, mixed, superactive, nonacid, mesic Fluvaquentic Endoaquepts), while Quilcene trials were on a Quilcene silt loam (Fine, mixed, mesic Aquic Dystric Xerochrepts). Although the amount of on-site precipitation received during these experiments is not available, average annual precipitation in Port Angeles is about half that in Quilcene (636 and 1,544 mm $yr^{-1}$, respectively) with average monthly precipitation totals in Port Angeles ranging from 33 to 68% of that in Quilcene (compiled from Western Regional Climate Center data 2013).

**Herbicide Experiment.** Herbicides were selected for testing based on their general efficacy against *Centaurea* species (Prather 2013). Herbicides were applied postemergence at one of two timings: early, when rosettes had not yet begun to bolt, or late, when nontreated plants were in the bud stage of growth immediately prior to flowers emerging from the heads. All treated plots were then treated again with the same herbicides in the autumn, so that all plots were treated twice in the same calendar year. Meadow knapweed plants at the autumn timing were no longer flowering, but foliage had not senesced and was still green in color. Plots measured 2.4 by 9.1 m (8 by 30 ft). All herbicides were applied using a $CO_2$-pressurized backpack sprayer equipped with a five-nozzle boom delivering 282 L $ha^{-1}$ (30 gal $ac^{-1}$) at 255 kPa (37 psi). Herbicides evaluated were glyphosate (Aquamaster®, 648 g ai $L^{-1}$ [5.4 lb ai $gal^{-1}$]) and Roundup Ultra®, 480 g ai $L^{-1}$, Monsanto Company, St. Louis, MO), dicamba + 2,4-D, dicamba + 2,4-D + MCPP (Weed-B-Gon®, The ORTHO Group, Columbus, OH), triclopyr ester + 2,4-D ester (Crossbow®, Dow AgroSciences LLC, Indianapolis, IN), clopyralid, clopyralid + 2,4-D, clopyralid + triclopyr, and imazapic. Herbicide rates are provided in Tables 1 and 2. Glyphosate (Aquamaster) was mixed with nonionic surfactant (NIS; Dyne-Amic®, Helena Chemical Company, Colliersville, TN) at 0.25%, v/v prior to application, while another glyphosate (Roundup Ultra) treatment was mixed with ammonium sulfate (AMS; J.T. Baker, Philipsburg, NJ) at 2%, wt/v prior to application. Imazapic was mixed with methylated seed oil (MSO; Sun-It II®, AGSCO, Grand Forks, ND) at 2.4 L $ha^{-1}$ prior to application. Early applications were made May 4, 2001 and April 16, 2004 for the first and second trials, respectively, late applications on June 21, 2001 and June 10, 2004, respectively, and autumn applications on September 27 of 2001 and 2004, respectively. Percent weed control was visually estimated (0 = no injury, 100 = dead plants) to the nearest 5% on the dates listed in Table 1.

**Herbicide/Mechanical Control Experiment.** Treatments in this experiment were (1) mowing both early and late, (2) herbicide applied early and late, (3) mowing applied early and herbicide applied late, (4) herbicide applied early and mowing applied late, (5) herbicide applied once late, (6) herbicide applied early and hand-weeding applied late, and (7) nontreated (check). Early application timing was when rosettes had not yet begun to bolt, and late was when nontreated plants were in early flowering stage of growth. Meadow knapweed plants at the late timing in this experiment were slightly more advanced into anthesis than noted for the late timing in the previously described herbicide experiment. The herbicide combination used for all treatments was dicamba + 2,4-D at 0.56 + 1.57 kg $ha^{-1}$ (5 + 1.4 lb $ac^{-1}$) applied with the same equipment used in the herbicide experiment. Plots measured 2.4 by 9.1 m. Mowing was accomplished using a sickle-bar mower that cut all vegetation to a height of 3 cm; clipped vegetation was left on the plots. Hand-weeding consisted of pulling all visible meadow knapweed plants from the soil with roots attached, as contrasted with only cutting the tops from the plants in mowed plots. Pulled meadow knapweed plants were bagged and removed from the site. Early treatments were applied June 20, 2002 and June 10, 2004 for the first and second trial, respectively, while late treatments were applied July 23, 2002 and August 2, 2004, respectively. Percent weed control was visually estimated as in the herbicide experiment on the dates listed in Table 1. Biomass of meadow knapweed and grass were sampled July 31 of 2003 and July 27, 2005 for the first and second trial, respectively. Single quadrats (70 by 50 cm) were placed in representative sections of each plot and all vegetation was clipped by hand at 2.5 cm above the soil. Meadow knapweed and grass were separated, dried at 50 C (122 F) for 3 d, and weighed. Perennial ryegrass (*Lolium perenne* L.) was the dominant grass species in both Port Angeles and Quilcene. Tall fescue (*Lolium arundinaceum* (Schreb.) S.J. Darbyshire) was also found in plots at both locations, while Port Angeles plots additionally contained sweet vernalgrass (*Anthoxanthum odoratum* L.).

**Statistics.** The experimental design for both experiments was a randomized complete block with four replicates. Lavene's test was performed on all data to assess homogeneity of residual variance while normality was assessed using Shapiro-Wilk tests using PROC UNIVARIATE of SAS (Statistical Analysis Software, Version 9.2, SAS Institute, Cary, NC). All data except the meadow knapweed biomass data from the 2004 to 2005 trial of the herbicide/mechanical control experiment met assumptions for ANOVA; variance in those data was successfully stabilized using a square root transformation prior to analysis. All data are presented as nontransformed means. PROC MIXED of SAS was used to analyze the data.



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Table 1. Meadow knapweed control after treatment with various herbicides alone and in combination (Herbicide Experiment, 2001 to 2002 trial; Port Angeles, WA).

| Treatment[a] | Rate | Control[b] | | | | |
|---|---|---|---|---|---|---|
| | | 6/21/01 | 9/27/01 | 4/24/02 | 6/20/02 | 8/28/02 |
| | kg ha$^{-1}$ | % | % | % | % | % |
| Early + autumn treatments | | | | | | |
| Clopyralid | 0.43 | 85 a | 65 a-d | 100 a | 100 a | 96 a |
| Clopyralid + 2,4-D | 0.21 + 1.12 | 73 a | 55 b-e | 100 a | 95 a | 85 ab |
| Dicamba + 2,4-D | 0.56 + 1.57 | 68 ab | 48 cde | 100 a | 95 a | 85 ab |
| Dicamba + 2,4-D + MCPP | 0.08 + 0.19 + 0.63 | 29 bc | 5 fg | 74 a | 48 bc | 20 cd |
| Glyphosate + NIS | 3.36 + 0.25 v/v | 31 bc | 0 g | 85 a | 86 ab | 45 bcd |
| Glyphosate | 3.36 | 30 bc | 0 g | 100 a | 88 a | 48 bcd |
| Glyphosate + AMS | 3.36 | 11 c | 0 g | 100 a | 92 a | 60 abc |
| Imazapic + MSO | 0.21 | 14 c | 5 fg | 16 b | 20 c | 16 cd |
| Triclopyr ester + 2,4-D ester | 0.84 + 1.68 | 58 ab | 30 efg | 96 a | 73 ab | 59 abc |
| Late + autumn treatments | | | | | | |
| Clopyralid | 0.43 | — | 80 abc | 100 a | 100 a | 100 a |
| Clopyralid + 2,4-D | 0.21 + 1.12 | — | 89 ab | 100 a | 99 a | 96 a |
| Dicamba + 2,4-D | 0.56 + 1.57 | — | 81 abc | 99 a | 85 ab | 81 ab |
| Dicamba + 2,4-D + MCPP | 0.08 + 0.19 + 0.63 | — | 70 a-d | 87 a | 68 ab | 48 bcd |
| Glyphosate + NIS | 3.36 + 0.25 v/v | — | 96 a | 100 a | 93 a | 59 abc |
| Glyphosate | 3.36 | — | 95 a | 100 a | 86 ab | 61 abc |
| Glyphosate + AMS | 3.36 | — | 97 a | 100 a | 90 ab | 59 abc |
| Imazapic + MSO | 0.21 | — | 36 def | 33 b | 23 c | 10 d |
| Triclopyr ester + 2,4-D ester | 0.84 + 1.68 | — | 79 abc | 100 a | 91 a | 89 ab |
| $HSD_{0.05}$ | | 40 | 35 | 39 | 39 | 48 |

[a] Each treatment applied twice: either rosette (May 4, 2001) or bolting (June 21, 2001) and in autumn (September 27, 2001). NIS = nonionic surfactant (DyneAmic) applied at 0.25%, v/v; AMS = ammonium sulfate applied at 2% wt/v; MSO = methylated seed oil (SunIt II) applied at 2.4 L ha$^{-1}$.

[b] Percent meadow knapweed control on June 21, 2001, September 27, 2001, April 24, 2002, June 20, 2002, and August 28, 2002. Means within a column followed by the same letter are not significantly different (Tukey's Honestly Significant Difference Procedure at $P \leq 0.05$).

Means for the herbicide experiment were separated using Fisher's Protected Least Significant Difference test ($P \leq 0.05$), while Tukey's honestly significant difference procedure (95% confidence level) was used for the herbicide/mechanical control experiment. The two trials of both experiments differed in nearly every measurement, so data were analyzed and results presented separately.

## Results and Discussion

**Herbicide Experiment.** In the 2001 to 2002 trial, control with early treatments with clopyralid, dicamba + 2,4-D, or triclopyr ester + 2,4-D ester exceeded other treatments at 7 weeks after rosettes were treated, ranging from 58 to 85% control (Table 1). Control from these treatments had declined to 30 to 65% by 5 months after rosette treatment, although the bolting applications resulted in 80 to 89% control for these treatments at 4 months after bud-stage treatment.

Meadow knapweed rosettes treated with dicamba + 2,4-D + MCPP displayed epinasty, but control from this treatment did not exceed 30% (Table 1). Bud-stage application resulted in 70% control at 4 months after treatment, indicating that timing played an important role in control with this herbicide combination, as did dose, when contrasting this treatment with the far better control achieved with the dicamba + 2,4-D treatment. In a similar manner, control with triclopyr ester + 2,4-D ester was poorer when applied to rosettes than when applied to bolting plants. Control with imazapic was poor regardless of timing.

Glyphosate was likely not as effective at the early timing as might usually be expected (Table 1) because applications were made prior to emergence of foliage of several meadow knapweed plants, as there was a surprising variability in



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Table 2. Meadow knapweed control after treatment with various herbicides alone and in combination (Herbicide Experiment, 2004 to 2005 trial; Quilcene, WA).

| Treatment[a] | Rate | Control[b] | | | | |
|---|---|---|---|---|---|---|
| | | 6/9/04 | 10/12/04 | 4/27/05 | 6/21/05 | 7/27/05 |
| | kg ha$^{-1}$ | % | % | % | % | % |
| Early + autumn treatments | | | | | | |
| Clopyralid | 0.43 | 99 a | 99 a | 100 a | 100 a | 100 a |
| Clopyralid + 2,4-D | 0.21 + 1.12 | 96 ab | 95 a | 100 a | 100 a | 100 a |
| Dicamba + 2,4-D | 0.56 + 1.57 | 95 ab | 86 a | 99 a | 100 a | 99 a |
| Glyphosate + NIS | 3.36 + 0.25 v/v | 89 ab | 31 b | 95 ab | 81 ab | 60 bcd |
| Glyphosate | 3.36 | 90 ab | 33 b | 95 ab | 75 abc | 70 abc |
| Glyphosate + AMS | 3.36 | 84 b | 23 b | 90 bc | 41 c | 34 d |
| Triclopyr ester + 2,4-D ester | 0.84 + 1.68 | 98 a | 86 a | 100 a | 99 a | 99 a |
| Triclopyr + clopyralid | 0.63 + 0.21 | 99 a | 96 a | 100 a | 100 a | 100 a |
| Late + autumn treatments | | | | | | |
| Clopyralid | 0.43 | — | 95 a | 100 a | 100 a | 100 a |
| Clopyralid + 2,4-D | 0.21 + 1.12 | — | 96 a | 100 a | 100 a | 99 a |
| Dicamba + 2,4-D | 0.56 + 1.57 | — | 83 a | 70 c | 55 bc | 55 cd |
| Glyphosate + NIS | 3.36 + 0.25 v/v | — | 96 a | 99 a | 79 ab | 80 abc |
| Glyphosate | 3.36 | — | 97 a | 97 ab | 68 abc | 81 abc |
| Glyphosate + AMS | 3.36 | — | 98 a | 99 a | 79 ab | 89 ab |
| Triclopyr ester + 2,4-D ester | 0.84 + 1.68 | — | 96 a | 86 b | 71 abc | 78 abc |
| Triclopyr + clopyralid | 0.63 + 0.21 | — | 97 a | 100 a | 99 a | 98 a |
| $HSD_{0.05}$ | | 14 | 22 | 13 | 34 | 31 |

[a] Each treatment applied twice: either rosette (April 16, 2004) or bolting (June 10, 2004) and in autumn (September 27, 2004). NIS = nonionic surfactant (DyneAmic) applied at 0.25%, v/v; AMS = ammonium sulfate applied at 2% wt/v.

[b] Percent meadow knapweed control on June 9, 2004, October 12, 2004, April 27, 2005, June 21, 2005, and July 27, 2005. Means within a column followed by the same letter are not significantly different (Tukey's Honestly Significant Difference Procedure at $P \leq 0.05$).

spring foliar emergence among meadow knapweed plants at this site. By 5 months after rosette treatment, control from these early-season glyphosate applications was negligible. The same glyphosate rates applied to bolting plants resulted in 95 to 97% meadow knapweed control at 4 months after treatment, indicating that properly-timed glyphosate can provide excellent initial control of this species.

Autumn treatments following either the rosette or bolting applications resulted in nearly complete meadow knapweed control in late April of the following year with all products except imazapic, or the rosette treatment with dicamba + 2,4-D + MCPP (Table 1). By June, control had dropped with nearly all treatments, although results had not changed appreciably from the previous evaluation. By August, however, only clopyralid alone or with 2,4-D, dicamba + 2,4-D applied to either rosettes or bolting plants and in autumn, and triclopyr ester + 2,4-D ester applied to bolting plants and in autumn were providing acceptable (81 to 100%) meadow knapweed control.

In the 2004 to 2005 trial, nearly every rosette treatment provided excellent meadow knapweed control by 7 weeks after treatment (Table 2). Although control did not differ among glyphosate treatments, glyphosate + AMS was not as effective as clopyralid, triclopyr ester + 2,4-D ester, or triclopyr + clopyralid at this timing. Clopyralid treatments, dicamba + 2,4-D, and triclopyr ester + 2,4-D ester applied to rosettes were providing 86 to 99% meadow knapweed control at 5 months after treatment, while all bolting plant treatments were providing a comparable level of weed control at 4 months after those treatments.

By the following April, dicamba + 2,4-D and triclopyr ester + 2-4-D applied bolting and in autumn and glyphosate + AMS applied to rosettes and in autumn were providing 70 to 90% control, while all other treatments were giving 95 to 100% control (Table 2). Control with glyphosate treatments had fallen to 81% or less by June while control with dicamba + 2,4-D and triclopyr ester + 2,4-D ester applied bolting and in autumn was 55 and



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Table 3. Meadow knapweed control after various combinations of mechanical control with dicamba + 2,4-D (Herbicide/Mechanical Control Experiment, 2002 to 2003 trial; Port Angeles, WA).

| | Control[b] | | Dry weight[c] | |
|---|---|---|---|---|
| Treatment[a] | 8/28/02 | 7/31/03 | Knapweed | Grass |
| | % | % | kg ha$^{-1}$ | kg ha$^{-1}$ |
| Mow/mow | 0 d | 10 c | 19,887 a | 1,061 b |
| Herb/herb | 65 b | 94 a | 306 b | 6,409 a |
| Mow/herb | 29 c | 78 b | 898 b | 5,343 a |
| Herb/mow | 98 a | 92 a | 1,219 b | 5,762 a |
| Herb late | 28 c | 92 a | 1,549 b | 5,309 a |
| Herb/hand-weed | 93 a | 95 a | 49 b | 7,736 a |
| Nontreated | — | — | 20,262 a | 1,061 b |
| $LSD_{0.05}$ | 15 | 14 | 10,821 | 2,981 |

[a] Treatments applied rosette (June 20, 2002) and/or early flowering (July 23, 2002). Mow = clipped with a cycle-bar mower; herb = herbicide (dicamba + 2,4-D at 0.56 + 1.57 kg ha$^{-1}$).

[b] Percent meadow knapweed control on August 28, 2002 and July 31, 2003. Means within a column followed by the same letter are not significantly different (Fisher's Protected LSD at $P \leq 0.05$).

[c] Meadow knapweed and grass sampled July 31, 2003. Means within a column followed by the same letter are not significantly different (Fisher's Protected LSD at $P \leq 0.05$).

71%, respectively. By the July evaluation, all treatments with clopyralid applied either to rosettes or bolting and in autumn and dicamba + 2,4-D and triclopyr ester + 2,4-D ester applied to rosettes and in autumn were still providing 98 to 100% meadow knapweed control; the only other treatment at that evaluation providing similar control was glyphosate + AMS applied bolting and in autumn.

These data indicate that meadow knapweed was most consistently controlled by clopyralid or clopyralid + 2,4-D at rosette or at bolting in both the 2001 to 2002 and 2004 to 2005 trials. Triclopyr + clopyralid was also an excellent treatment in the 2004 to 2005 trial, but this result is considered preliminary because a second year of performance data is not available. Dicamba + 2,4-D and triclopyr ester + 2,4-D ester also showed good activity on meadow knapweed, although these treatments were more variable in efficacy. Control with dicamba + 2,4-D at rosette or bolting was statistically equal to the best treatments in the 2001 to 2002 trial, but was far superior when applied to rosettes and in autumn than when applied at bolting and in autumn in the 2004 to 2005 trial. Control with triclopyr ester + 2,4-D ester was equal to the best treatments when applied at bolting and in autumn in the 2001 to 2002 trial and at rosette and in autumn in the 2004 to 2005 trial. Meadow knapweed control was transitory when using glyphosate. It appears, therefore, that herbicides recommended to control other knapweed species also provide acceptable control of meadow knapweed.

**Herbicide/Mechanical Control Experiment.** In the 2002 to 2003 trial, meadow knapweed control in August was 98 or 93% with dicamba + 2,4-D applied to rosettes followed by either mowing or hand-weeding, respectively (Table 3). By July of the following year, control in all herbicide-treated plots exceeded 90%, except when meadow knapweed was mowed in June and sprayed in July (78% control). Mowing twice the previous year had only a slight effect on meadow knapweed (10% control).

Meadow knapweed biomass in July of the year after treatment in the 2002 to 2003 trial was similar in plots mowed twice and in nontreated plots (Table 3). There was not a significant difference in meadow knapweed biomass among treatments using herbicide, although the rosette treatments followed by hand-weeding tended to produce the least biomass, followed by plots treated with herbicide twice. Grass biomass was essentially complementary to meadow knapweed biomass; that is, herbicide-treated plots produced substantially more grass than nontreated plots or plots mowed twice. Grass production exceeded meadow knapweed biomass in all herbicide-treated plots.

Meadow knapweed response to herbicides and mechanical control was less clear in the 2004 to 2005 trial (Table 4). Control in September was maximized when rosettes were treated with dicamba + 2,4-D followed mowing or hand-weeding (100 and 99%, respectively) or when these herbicides were applied twice (73%). Control from dicamba + 2,4-D applied twice was statistically equal to mowing twice or treating once early flowering (59%). By July of the year after treatment, meadow knapweed control was variable, with treatments giving 49 to 90% control being statistically similar. Meadow knapweed biomass at that evaluation was reduced in plots treated with dicamba + 2,4-D twice or once early flowering. The trend in the meadow knapweed control and biomass data was for dicamba + 2,4-D treatments to be more effective than mowing twice, and that these herbicides were generally more effective when applied twice or after mowing. Grass biomass was maximized when rosettes were mowed and treated with dicamba + 2,4-D at early flowering or when treated twice with herbicide; these were the only treatments where grass biomass exceeded meadow knapweed biomass. Treating with herbicide followed by hand-weeding resulted in similar grass biomass as two herbicide applications, but resulted in roughly equal grass and meadow knapweed biomass production.

The differential control of meadow knapweed with dicamba + 2,4-D between the two trials of the herbicide/



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Table 4. Meadow knapweed control after various combinations of mechanical control with dicamba + 2,4-D (Herbicide/Mechanical Control Experiment, 2004 to 2005 trial; Quilcene, WA).

| | Control[b] | | Dry weight[c] | |
|---|---|---|---|---|
| Treatment[a] | 9/1/04 | 7/27/05 | Knapweed | Grass |
| | % | % | kg ha$^{-1}$ | kg ha$^{-1}$ |
| Mow/mow | 59 bc | 44 bc | 15,398 ab | 6,922 c |
| Herb/herb | 73 ab | 83 ab | 5,590 bc | 14,046 ab |
| Mow/herb | 41 c | 90 a | 1,801 c | 15,797 a |
| Herb/mow | 100 a | 34 c | 12,605 ab | 6,182 c |
| Herb late | 59 bc | 59 abc | 12,142 ab | 8,219 c |
| Herb/hand-weed | 99 a | 49 abc | 10,588 ab | 9,325 bc |
| Nontreated | — | — | 23,691 a | 7,593 c |
| $LSD_{0.05}$ | 28 | 41 | 2,655 | 5,634 |

[a] Treatments applied rosette (June 10, 2004) and/or early flowering (August 2, 2004). Mow = clipped with a cycle-bar mower; herb = herbicide (dicamba + 2,4-D at 0.56 + 1.57 kg ha$^{-1}$).

[b] Percent meadow knapweed control on September 1, 2004 and July 27, 2005. Means within a column followed by the same letter are not significantly different (Fisher's Protected LSD at $P \leq 0.05$).

[c] Meadow knapweed and grass sampled July 27, 2005. Means within a column followed by the same letter are not significantly different (Fisher's Protected LSD at $P \leq 0.05$).

mechanical experiment warrants more discussion. In the 2002 to 2003 trial, control in July of the year after treatment was poorer when these herbicides were applied after early mowing, but the only treatment not providing adequate meadow knapweed control in that trial was mowing twice with no herbicide application. This contrasts with the 2004 to 2005 trial, where meadow knapweed control was numerically improved when the herbicides were applied in early flowering after rosettes were mowed, or when meadow knapweed was treated twice with herbicide. Since meadow knapweed stage of growth at the times of herbicide application was the same between both trials, the observed difference in control was due to differences in weather conditions during 2002 and 2004, differences between the meadow knapweed populations at the two sites, or a combination of these factors. The effect was also observed with dicamba + 2,4-D in the herbicide experiment at the last evaluation of the year following treatment, where the rosette + autumn and bolting + autumn treatments in the 2001 to 2002 trial resulted in 85 and 81% control, respectively, compared to 99 and 55% control from the same timings, respectively, in the 2004 to 2005 trial. This provides evidence that the meadow knapweed population near Port Angeles (2001 and 2002 applications) was more sensitive to dicamba + 2,4-D than the population near Quilcene (2004 applications). This apparent lessened sensitivity to dicamba + 2,4-D at Quilcene was offset by early mowing followed by treating regrowth, or by two herbicide applications, resulting in 90 and 83% control, respectively. Whether this difference is due to genetic differences in the population or due to environmental conditions such as soil type, depth, or aspect, is not clear.

In conclusion, as with other knapweeds, herbicide treatments containing clopyralid provided the most consistent control of meadow knapweed. Other auxinic herbicides such as 2,4-D, dicamba, and triclopyr were active on the species, although performance was more variable. Glyphosate provided short-term meadow knapweed control, although use of that herbicide is normally not appropriate in pastures, unless reseeding with a pasture grass is being planned; glyphosate may be an excellent choice for meadow knapweed control in other noncrop areas. These same herbicides are often recommended at similar rates for control of other knapweed species, indicating that meadow knapweed responds similarly to other *Centaurea* species to herbicide treatment. Mowing did not greatly aid or hinder meadow knapweed control when used in conjunction with dicamba + 2,4-D treatments, although two mowings without herbicide was ineffective for control of this hybrid. Two auxinic herbicides not available to the authors for testing during these trials are aminopyralid and aminocyclopyrachlor. As of 2013, aminopyralid is registered for control of other knapweed species in the United States and Canada, while aminocyclopyrachlor is registered for knapweed control in the United States only. Given the results from these experiments, it is not unreasonable to believe these herbicides will also provide effective control of meadow knapweed; such treatments need to be evaluated on meadow knapweed before they can be recommended for its control, however.

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