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Testing Integrated Management Strategies for Tall Buttercup (*Ranunculus acris*) in Irrigated Hayfield Meadows

Hally K. Strevey and Jane M. Mangold*

Tall buttercup is an invasive forb that has been reported in all but eight states and one Canadian province. The species has been of concern in Montana where it has invaded over 8,300 ha, and it has been particularly problematic in irrigated hayfield meadows that are used for forage production. This study sought to develop an integrated management strategy to control tall buttercup while maintaining forage production. Research was conducted over 2 yr at flood-irrigated and subirrigated hayfield meadows near Twin Bridges, MT. Treatments were randomly applied in a split-plot design with four replications at both sites. Herbicide treatments occurred at the whole-plot level: nonsprayed, aminopyralid (172 g ai ha^{-1}), aminocyclopyrachlor + chlorsulfuron (83 g ai ha^{-1} + 33 g ai ha^{-1}), and dicamba (981 g ai ha^{-1}). Split plots consisted of mowing and fertilization (28 kg N ha^{-1}). All herbicides provided up to 2 yr of tall buttercup control at both sites. In the second year, aminocyclopyrachlor + chlorsulfuron and aminopyralid reduced tall buttercup by 93% and 96%, respectively, for the subirrigated and flood-irrigated sites. At the subirrigated site, mowing reduced tall buttercup by 71%, and fertilization reduced it by 57%. Forage decreased following aminocyclopyrachlor + chlorsulfuron treatments. The integration of herbicide, mowing, and fertilization did not improve tall buttercup control.

Nomenclature: Aminocyclopyrachlor; aminopyralid; chlorsulfuron; dicamba; tall buttercup, *Ranunculus acris* L. RANAC.

Key words: Fertilization, forage production, integrated weed management, invasive plants, mowing.

Tall buttercup (*Ranunculus acris* L.) is a perennial invasive forb native to central and northeastern Europe (Coles 1971). It occurs in moist habitats, including pastures, grasslands, and irrigated meadows (Lamoureaux and Bourdôt 2007; Jacobs et al. 2010). Tall buttercup was first reported in North America in the early 1900s. It has since been found in all but eight states and one Canadian Province (USDA–NRCS 2013). Tall buttercup has been a problematic invader in New Zealand for many years, particularly in the dairy farming regions of the Northern Island (Lamoureaux and Bourdôt 2007). In these regions, tall buttercup is highly competitive and has been reported to infest over 50% of pasture areas, resulting in an annual economic loss of NZ$156 million to the dairy industry alone (Bourdôt et al. 2003).

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Tall buttercup produces the toxic glycoside ranunculin, a bound form of protoanemonin found in members of the Ranunculaceae family (Bonora et al. 1987). If tall buttercup is consumed by grazing animals, an enzymatic breakdown of the glycoside ranunculin occurs, and the vesicant, protoanemonin forms (Harper and Sagar 1953). Protoanemonin can cause blistering of the lips and tongue, irritation of the digestive tract, respiratory failure, ventricular fibrillation, and death in some cases (Cheeke 1998). However, the glycoside ranunculin gives tall buttercup a bitter flavor, so the plant is typically avoided by livestock (Lamoureaux and Bourdôt 2007), thereby reducing the carrying capacity of infested pastures (Harper 1957).

Phenoxy herbicides such as MCPA and MCPB have been used to control tall buttercup in New Zealand (Bourdôt and Hurrell 1991; Tuckett 1961); and paraquat, diquat, 2,4-D, and MCPA have been used in field experiments in Czechoslovakia, Russia, Norway, and Slovakia (Lamoureaux and Bourdôt 2007). However, tall buttercup has developed resistance to some of these herbicides, and that resistance is positively correlated with frequency of historical applications (Bourdôt et al. 1990; Bourdôt and Hurrell 1991).

Management Implications

Tall buttercup has been a problematic invader in New Zealand for many years. In North America the species has recently been of concern, especially in Montana where it is believed to reduce forage production in hayfield meadows. However, there are no published studies on tall buttercup management in North America, and landowners have little guidance about how to control the species, while maintaining productivity and plant diversity. In this study, we sought to develop an integrated management strategy to control tall buttercup while encouraging the growth of desirable forage plants, including perennial grasses and clovers. We used two study sites, one in a subirrigated hayfield and a second in a flood-irrigated hayfield in western Montana. We tested four herbicide treatments, including nonsprayed, aminopyralid (172 g ai ha^{-1}), aminocyclopyrachlor + chlorsulfuron (83 g ai ha^{-1} + 33 g ai ha^{-1}), and dicamba (981 g ai ha^{-1}), mowing, and fertilization (28 kg N ha^{-1}), applied individually and in all possible combinations. Aminopyralid and aminocyclopyrachlor + chlorsulfuron most effectively reduced tall buttercup biomass. Dicamba also reduced tall buttercup compared to the nonsprayed treatment, but was not as effective as the other two herbicides. At the subirrigated site, mowing and fertilization used individually reduced tall buttercup. However, mowing or fertilization at the flood-irrigated site did not reduce tall buttercup, and their combination did not provide control at either site. Moreover, the integration of herbicides with mowing and fertilization did not improve tall buttercup control. Aminocyclopyrachlor + chlorsulfuron reduced perennial grasses at both sites, and all herbicides reduced clover, an important forage component of hayfield meadows, compared to nonsprayed plots across both sites. Although combinations of mowing and fertilization with or without herbicides did not improve control of tall buttercup over the use of herbicides alone, long-term integrated management can reduce selection pressure that could lead to herbicide resistance.

Because of tall buttercup's capacity to develop herbicide resistance, the use of an integrated management strategy might prevent the likelihood of resistance developing in North America. Furthermore, integrated management can also encourage the growth and fitness of desired species in a way that meets environmental and economic priorities (Jacobs et al. 2006). Additional control methods include mowing and fertilizer application (Lamoureaux and Bourdôt 2007). Mowing effectively reduced tall buttercup flowering in red fescue-dominated meadows in Russia (Rabotnov and Saurina 1971). Additional studies in Scotland (Ford 1996), Austria, and Dagastan (Andreev and Gamidov 1985; Lamoureaux and Bourdôt 2007) have shown reductions in tall buttercup flowering following mowing. Fertilizing with nitrogen (N), phosphorus (P), and potassium (K) increased palatable grasses and decreased tall buttercup in deteriorated pastures in Russia (Lamoureaux and Bourdôt 2007), and N fertilizer applied to grasslands in Greece reduced the relative abundance of tall buttercup (Tzialla et al. 2002). However, fertilization in other countries had little impact on tall buttercup abundance (Brown 1993; Lamoureaux and Bourdôt 2007; Leskosek 1996).

Tall buttercup is becoming a concern in North America, especially in Montana where it has invaded over 8,300 ha (20,510 ac) (Montana Noxious Weed Summit Advisory Council 2008), and was listed as a noxious weed in 2003. Landowners with tall buttercup on their property are required to develop a management plan for it; however, because there has been minimal research conducted on tall buttercup management in North America, landowners have little guidance about how to control it, while maintaining productivity and plant diversity. Given tall buttercup's history of developing herbicide resistance in New Zealand (Lamoureaux and Bourdôt 2007), research on integrated management is necessary to develop techniques to control the species and to prevent it from becoming even more widespread.

The objective of this study was to test tall buttercup management strategies, including herbicides, mowing, and fertilization alone and in combination with each other. These management strategies were selected to specifically target tall buttercup, while encouraging growth of desirable pasture plants. Tall buttercup was predicted to decrease in response to control treatments, with the greatest control coming from the combination of herbicides, mowing, and fertilization. Desired perennial grasses were predicted to increase following treatments, and the response of desired forbs would vary depending on species and type of treatment.

Materials and Methods

Site Description. Two study sites were selected approximately 16 km (10 mi) southwest from Twin Bridges, MT. Sites were located in irrigated hayfield meadows that were dominated by nonnative perennial grasses and clovers used for cattle forage. Sites were chosen based upon tall buttercup density and landowner cooperation. Land management practices on both study sites occurred as usual throughout the project's duration and included cattle grazing in the early summer and haying in the late summer; however the irrigation practices varied between the two sites. In midsummer, one site is subirrigated, whereas the second site is flood irrigated. Subirrigation is a type of irrigation that provides water to the plants' root zone from below the soil surface (Michigan State University Extension 2012), and flood irrigation is a technique in which the field is flooded and water is allowed to soak into the soil (USGS 2014). Because of the varying irrigation practices, sites will be referred to as subirrigated or flood irrigated. Sites were located approximately 3 km from one other. Elevation at the subirrigated site (45°29′25.07″N, 112°26′26.76″W) and the flood-irrigated site (45°29′51.90″N, 112°24′06.77″W) is 1,436 m (4,711 ft) and 1,448 m, respectively. Soil at both sites is a sandy clay loam of the Rivra-Ryell Havre complex with a pH of 7.6 to 7.8 (USDA–NRCS 2008). From 1950 to 2013, precipitation and temperature have averaged 24.2 cm (9.5 in) and 14.6 C (58 F), respectively, at both sites (NOAA–NCDC 2002). Both sites had a diversity of perennial grass, grass-like forb, and exotic forb species. Some of the most common species found at both sites included creeping meadow foxtail (*Alopecurus arundinaceus* Poir.), timothy (*Phleum pratense* L.), Canada bluegrass (*Poa compressa* L.), Kentucky bluegrass (*Poa pratensis* L.), meadow brome (*Bromus biebersteinii* Roem & Schult.), sedges (*Carex* spp.), rushes (*Juncus* spp.), red and white clover (*Trifolium* spp.), perennial sowthistle (*Sonchus arvensis* L.), and dandelion (*Taraxacum officinale* G. H. Weber ex Wiggers). Prevalence of tall buttercup ranged from 1 to 9% cover at the subirrigated site and 2 to18% cover at the flood-irrigated site.

Experimental Design. The study followed a split-plot design with four replicates at each site. Treatments were applied on June 20 and June 21, 2012. Many of the mature tall buttercup plants at both sites had begun flowering when treatments were applied. Whole plots were 12.2 m by 9.1 m and placed 5 m apart from one another to prevent effects from adjacent treatments. One of four different herbicide treatments was randomly assigned to each whole plot, including (1) nonsprayed; (2) aminopyralid (AMP) (Milestone®, 172 g ai ha^{-1} (5 oz ac^{-1}), Dow AgroSciences, 9330 Zionsville Road Indianapolis, IN 46268); (3) aminocylopyrachlor + chlorsulfuron (AMCP+CHL) (Perspective®, 83 g ai ha^{-1} + 33 g ai ha^{-1}, du Pont de Nemours and Company, 1007 Market Street, Wilmington, DE 19898); and (4) dicamba (DIC) (Vanquish®, 981 g ai ha^{-1}, Syngenta Canada, Inc., 140 Research Lane, Research Park, Guelph Ontario, N1G 4Z3, Canada). All herbicide treatments were applied with a nonionic surfactant at 0.1% v/v herbicide solution. Within each whole plot were four 3 m by 9 m split plots. One of four different treatments were randomly assigned to each split plot, including (1) mowing, (2) fertilization at 28 kg N ha^{-1} (25 lb N ac^{-1}) (Scotts® Lawn Pro®, 26–0–3, The Scotts Company LLC, 14111 Scottslawn Road, Marysville, OH 43040); (3) mowing plus fertilization; and (4) nontreated control. Mowing was applied before any other treatment on June 20, 2012 using a mulching push mower (Husqvarna 5521P, Husqvarna Professional Products, Inc., 9335 Harris Corner Parkway Suite 500, Charlotte, NC 28269). Vegetation was mowed to a height of 15 cm, and clippings were removed from each split plot. Mowing was completed prior to applying herbicides in an attempt to increase herbicide contact on the basal leaves of both mature and seedling tall buttercup plants. Following mowing, fertilizer was hand broadcasted in the assigned split plots, and herbicides were applied last to the whole plots using a CO_2-powered 3.3-m boom sprayer delivering 157 L ha^{-1} (102 gal ac^{-1}) water at 3 kg cm^{-2} (2.5 lb in^{-2}) pressure.

Vegetation Sampling. Plots were sampled during peak standing biomass in late July 2012 and 2013, approximately 1 mo and 1 yr, respectively, after treatment. The biomass sampled in 2012 was produced prior to treatment application. Three 20 cm by 50 cm Daubenmire (1959) frames were randomly placed in each split plot. Biomass was clipped by functional group approximately 1.3 cm above the soil surface. Functional groups included tall buttercup (TB), perennial grasses (PG), exotic forbs (EF), and grass-like species including sedges and rushes (GL). Biomass samples were dried at 65 C for a minimum of 72 h to obtain dry plant biomass to the nearest 0.1 g (0.004 oz).

Statistical Analyses. To determine the effects of herbicide, mowing, and fertilizer treatments on biomass of each functional group across years, split-plot repeated measures analysis of variance (ANOVA) was conducted using RStudio 0.98.501 (R Core Team 2012). Response variables were natural log (ln) transformed to meet assumptions of normality and constant variance. Initial models indicated that sites differed in response to treatment ($P < 0.05$), therefore sites were analyzed separately. When significant main effects or interactions were found ($P \leq 0.05$), means separation tests were performed using Conventional Tukey's Test using the R package TukeyC ($\alpha \leq 0.05$) (Faria et al. 2013). Nontransformed means are presented for ease of interpretation.

Results and Discussion

Herbicides. Herbicide treatments reduced tall buttercup biomass; however, the effect varied between year and site (Table 1). At the subirrigated site in 2012, application of all three herbicides resulted in tall buttercup biomass similar to the nonsprayed treatment (Figure 1A). The AMCP+CHL treatment had 8.4 $\pm$ 1.5 g m^{-2}, AMP had 10.1 $\pm$ 3.1 g m^{-2}, DIC had 6.6 $\pm$ 1.7 g m^{-2}, and the nonsprayed treatment had 11.7 $\pm$ 6.9 g m^{-2} of tall buttercup. However, in 2013, all three herbicides reduced biomass relative to the nonsprayed treatment. AMCP+CHL and AMP were the most effective in tall buttercup control (0.7 $\pm$ 0.4 g m^{-2} and 0.5 $\pm$ 0.3 g m^{-2}, respectively). DIC also reduced tall buttercup, but the reduction was not as large as those treated with the other two herbicides (Figure 1A).

At the flood-irrigated site, all three herbicides reduced tall buttercup biomass relative to the nonsprayed treatment in 2012 (Figure 1B). Biomass in the nonsprayed treatment was 42 $\pm$ 8.1 g m^{-2}, whereas AMCP+CHL and AMP decreased tall buttercup biomass to 6.5 $\pm$ 2.1 g m^{-2} and 6.3 $\pm$ 1.0 g m^{-2}, respectively, followed by DIC at 11 $\pm$ 2.1 g m^{-2}. In 2013, AMCP + CHL and AMP reduced tall buttercup biomass to the greatest extent compared to the nonsprayed

Table 1. P values for treatment effects on functional group biomass from the subirrigated and flood-irrigated sites. Significant P values (< 0.05) are indicated in bold.

Parameter[a]	df	Subirrigated[a] TB	PG	GL	EF	Flood irrigated[a] TB	PG	GL	EF
Herb	3	**< 0.001**	**< 0.001**	**0.021**	0.118	**< 0.001**	**< 0.001**	0.675	**< 0.001**
Fert/Mow	3	**0.037**	0.242	0.112	0.069	0.789	0.546	0.065	0.721
Herb*Fert/Mow	9	0.207	0.261	0.763	0.266	0.444	0.989	0.312	0.241
Year	1	**< 0.001**	**< 0.001**	0.626	**< 0.001**	**< 0.001**	**< 0.001**	0.731	**< 0.001**
Herb*Year	3	**< 0.001**	**< 0.001**	0.053	0.156	**< 0.001**	**< 0.001**	0.77	**< 0.001**
Fert/Mow*Year	3	0.708	0.239	0.277	0.372	0.21	0.142	0.698	0.682
Herb*Fert/Mow*Year	9	0.686	0.171	0.784	0.165	0.876	0.951	0.829	0.787

[a] Abbreviations: TB, tall buttercup (*Ranunculus acris*); PG, perennial grasses; GL, grass-like species; EF, exotic forbs; Herb, herbicides; Fert, fertilization; Mow, mowing.

treatment (0.2 ± 0.1 g m^{-2} and 0.3 ± 0.2 g m^{-2}, respectively). Tall buttercup biomass in the DIC treatment was higher than in the other two herbicide treatments, yet still less than in the nonsprayed treatment (12 ± 3.4 g m^{-2}) (Figure 1B).

In 2012, the herbicide treatments did not control tall buttercup at the subirrigated site, but did provide control at the flood-irrigated site. The flood-irrigated site was more heavily grazed in 2012 when treatments were applied. Grazing animals typically avoid consuming tall buttercup (Lamoureaux and Bourdôt 2007). Because of grazing, it is possible that the tall buttercup foliage was subject to better herbicide contact because the more palatable vegetation was grazed around the tall buttercup plants. In addition, it is possible that the different irrigation regimes influenced treatment results. Soil moisture is more consistent in a subirrigated system vs. a flood-irrigated system, and it might have enabled tall buttercup to recover from the herbicide treatments in the first year. In a greenhouse study where tall buttercup seedlings were grown under different soil moisture conditions, seedling emergence and growth was higher when soil moisture was maintained at 50% vs. 100% field capacity (Strevey 2014). However, because we were unable to control grazing and irrigation, it is difficult to predict the extent to which these two management practices impacted our results.

As predicted, all three herbicides provided up to 2 yr of tall buttercup control. When examining the overall effectiveness of these herbicides for tall buttercup control across 2012 and 2013 and between the two sites, both AMP and AMCP+CHL reduced tall buttercup biomass to the greatest extent. DIC also reduced biomass, but plots with this treatment typically had higher amounts of tall buttercup relative to the other herbicide treatments. AMCP+CHL can remain active in the soil for at least 2 yr (Westra et al. 2008) and has a half-life ranging from 22 to 126 d (Finkelstein et al. 2008).

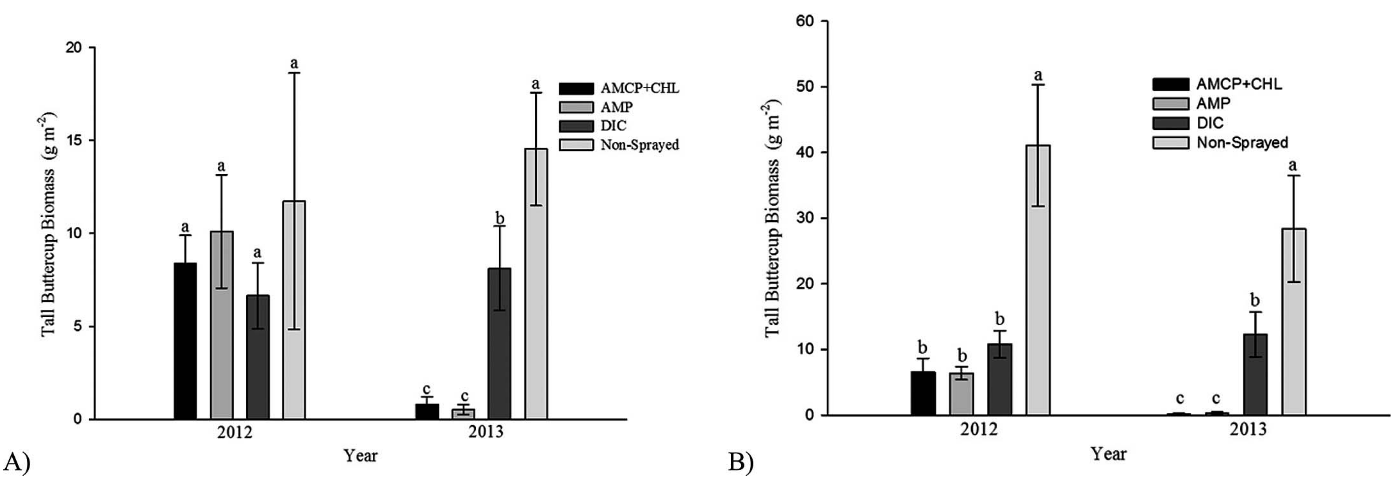

Figure 1. Tall buttercup biomass as affected by herbicide and year at (A) the subirrigated site and (B) the flood-irrigated site. Error bars indicate 1 standard error (SE) of the mean. Lowercase letters indicate means that are different within a herbicide treatment among year 2012 or 2013. Abbreviations: AMCP+CHL, aminocyclopyrachlor plus chlorsulfuron; AMP, aminopyralid; DIC, dicamba.

AMP has a shorter half-life of 30 d but is relatively immobile in the soil, so it typically stays within the upper 30 cm of the soil profile (Hartzler 2006). The long half-life of AMCP+CHL and the increased persistence in the soil of AMP likely resulted in better tall buttercup control when compared to DIC, whose half-life has been shown to be as short as 17 d (Altom and Stritzke 1973; Krueger et al. 1991).

Currently, Milestone (AMP) and Clarity® (DIC) are labeled for tall buttercup control in range and pasture (Anonymous 2005, 2010). Our results support the findings from a herbicide efficacy trial conducted in a subirrigated meadow in 2005 in Montana. Milestone was applied at two rates (103 g ai ha^{-1} and 172 g ai ha^{-1}) and two application timings, including a summer application in June and a fall application in September. One year after treatment, both summer and fall applications at 103 or 172 g ai ha^{-1} provided between 80 and 100% control of tall buttercup (C. Duncan, personal communication, 2014). Beyond personal communication, we found no other published documentation of tall buttercup control in the United States, which suggests that additional published research would help in the development of best practices for tall buttercup control with herbicides.

Exotic forbs responded to the herbicide treatments in a similar manner to tall buttercup at the flood-irrigated site. However, at the subirrigated site, exotic forb biomass only varied by year (Table 1). In 2012, exotic forb biomass was 24 $\pm$ 3.2 g m^{-2}, and in 2013, biomass decreased to 19 $\pm$ 3.1 g m^{-2}. At the flood-irrigated site, exotic forb biomass was found to be different between herbicide treatments and year (Table 1). AMCP+CHL, AMP, and DIC all reduced exotic forb biomass relative to the nonsprayed treatment in 2012 (Figure 2). Similarly in 2013, all herbicides decreased the biomass of exotic forbs, with AMCP+CHL reducing exotic forbs to the greatest extent followed by AMP and DIC (Figure 2).

Desired exotic forbs, including red and white clover, did not vary in their response to herbicide treatments as was predicted. From a management perspective, nontarget effects on exotic forbs other than tall buttercup might be both beneficial and detrimental to forage production. Reductions to some exotic forbs such as dandelion and sowthistle are advantageous; however, decreases in red and white clover following herbicide treatments is not desirable for forage production. Land managers must determine if the benefits of reducing the prevalence of tall buttercup outweigh the nontarget effects of the herbicide treatments on desirable clover species (Crone et al. 2009).

As with tall buttercup and exotic forbs, herbicide treatments also influenced perennial grasses. At the subirrigated site, perennial grass biomass varied by herbicide treatment and year (Table 1). In 2012, AMCP+CHL reduced perennial grass biomass relative to the nonsprayed treatment, whereas AMP and DIC had similar perennial grass biomass as the nonsprayed treatment (Figure 3A). By 2013, perennial grass biomass increased in the AMP and DIC treatments compared to the nonsprayed treatment, but biomass of the AMCP+CHL treatment remained lower than the nonsprayed treatment (Figure 3A). Likewise, at the flood-irrigated site, perennial grass biomass differed between herbicide treatment and year (Table 1). In 2012, AMCP+CHL decreased grass biomass, whereas AMP and DIC had similar perennial grass biomass as the nonsprayed treatment (Figure 3B). In 2013, AMCP+CHL had the lowest perennial grass biomass, and AMP and DIC remained similar to the nonsprayed treatment (Figure 3B).

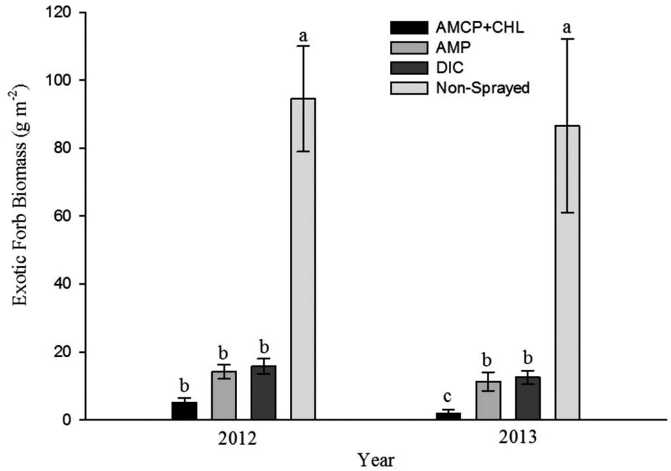

Figure 2. Exotic forb biomass as affected by herbicide and year at the flood-irrigated site. Error bars indicate 1 standard error (SE) of the mean. Lowercase letters indicate means that are different within a herbicide treatment among year 2012 or 2013. Abbreviations: AMCP+CHL, aminocyclopyrachlor plus chlorsulfuron; AMP, aminopyralid; DIC, dicamba.

In the irrigated meadows where tall buttercup invades, perennial grasses are the most important species for hay forage. We hypothesized that the herbicides utilized in this study would decrease tall buttercup and increase perennial grasses. At both sites, the opposite was observed following the application of AMCP+CHL, where perennial grass biomass decreased. Any decrease in perennial grasses following herbicide application is not a desirable outcome for forage production. This herbicide treatment was applied as Perspective® because it contains aminocyclopyrachlor (AMCP), the target active ingredient to control tall buttercup. However, both active ingredients of Perspective®, including AMCP and chlorsulfuron (CHL) are used to control certain grass species such as Kentucky bluegrass (*Poa pratensis*), ryegrass (*Lolium* spp.), and fescue grasses (*Festuca* spp.) (Derr 2012). Our results support those of Wallace and Prather (2010) who also documented grass injury in response to Perspective®.

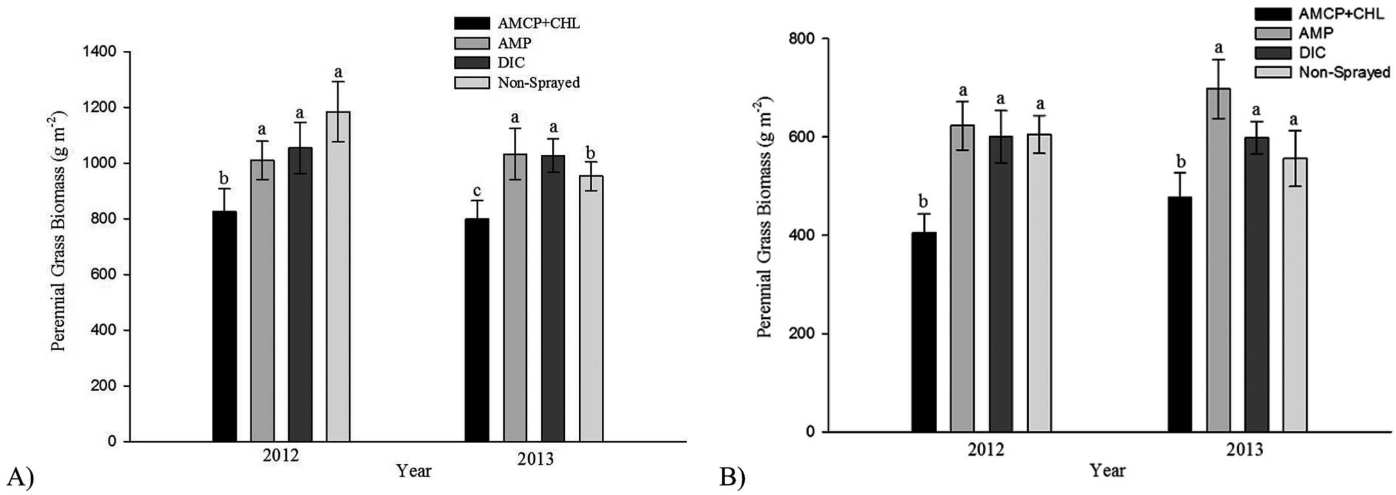

Figure 3. Perennial grass biomass as affected by herbicide and year at (A) the subirrigated site and (B) the flood-irrigated site. Error bars indicate 1 standard error (SE) of the mean. Lowercase letters indicate means that are different within a herbicide treatment among year 2012 or 2013. Abbreviations: AMCP+CHL, aminocyclopyrachlor plus chlorsulfuron; AMP, aminopyralid; DIC, dicamba.

In contrast to AMCP+CHL, both AMP and DIC either maintained or increased perennial grass abundance as was predicted. In fact, at the subirrigated site, AMP and DIC increased perennial grasses relative to the nonsprayed treatment by about 70 g m^{-2} the year following treatment (Figure 3A). This finding might be attributed to a decrease in other species, including tall buttercup and exotic forbs, which allowed the perennial grasses to utilize essential plant resources (i.e., light, nutrients, and water) that would otherwise have been used by exotic forbs.

Biomass of grass-like species responded to herbicide treatment at the subirrigated site (Table 1). The nonsprayed treatment had 164 $\pm$ 32 g m^{-2} of grass-like species. AMP- and DIC-treated plots had similar grass-like biomass as the nonsprayed treatment with 126 $\pm$ 10 g m^{-2} and 133 $\pm$ 20 g m^{-2}, respectively. Grass-like biomass was the highest in the AMCP+CHL treatment plots with 207 $\pm$ 25 g m^{-2}. At the flood-irrigated site there was no effect of herbicide treatments on grass-like biomass (Table 1).

Although perennial grass biomass decreased following the AMCP+CHL treatments (Figures 3A and 3B), grass-like species increased following this treatment. As the dominant perennial grass species decreased in response to AMCP+CHL, it is likely that grass-like species filled the open space. The increase in grass-like species is not considered a desirable outcome for forage production (D. Ashcraft and P. Novich, personal communication, 2012). Grass-like species including sedges and rushes are morphologically different than perennial grasses. Their surface area is smaller, and they are often found in bunches, unlike rhizomatous perennial grasses that are typically dominant. Rushes in particular are thick and wiry and do not produce as much biomass as perennial grasses. These results indicate that land managers should use caution if choosing AMCP+CHL to control tall buttercup in irrigated hayfield meadows due to its nontarget effects.

Mowing and Fertilization. Across both years at the subirrigated site (Table 1), mowing reduced tall buttercup biomass to 4.1 $\pm$ 0.9 g m^{-2} relative to the control (no herbicide, mowing, or fertilization) that had 14.1 $\pm$ 4.6 g m^{-2} of tall buttercup. Prior studies in other regions have found mowing to successfully control tall buttercup (Andreev and Gamidov 1985; Ford 1996; Lamoureaux and Bourdôt 2007), and that frequent cutting reduced both the flowering and vigor of the plant (Harper 1957). However, at the flood-irrigated site, mowing did not provide control. Due to the inconsistent results between sites, mowing might not be a reliable control method for tall buttercup in irrigated hayfield meadows.

Across both years at the subirrigated site (Table 1), fertilization reduced tall buttercup to 6.1 $\pm$ 1.2 g m^{-2} compared to the control that had 14.1 $\pm$ 4.6 g m^{-2}. Tall buttercup control, along with an increased abundance of desired species following fertilization, has been observed in several studies (Lamoureaux and Bourdôt 2007; Tzialla et al. 2002). In contrast, at the flood-irrigated site, fertilization did not provide control of tall buttercup (Table 1). It is possible that tall buttercup control was observed at the subirrigated site due to its relatively low density at the site when compared to the flood-irrigated site. DiTomaso (1995) found that when weed densities were low, adding N fertilizer increased crop yield over the invasive forb and made the crop a more vigorous competitor. However, due to the inconsistent results between sites, we do not recommend applying N fertilizer to control tall buttercup in irrigated hayfields until further research would suggest otherwise.

In previous tall buttercup control studies, fertilization or mowing alone or in combination promoted the competitiveness and growth of perennial grasses over tall buttercup (Andreev and Gamidov 1985; Ford 1996; Lamoureaux and Bourdôt 2007). However, we saw no effect of the mowing or fertilization treatments on perennial grasses at either site (Table 1). Due to our inconsistent results, the potential of these strategies to fit into an integrated management scheme remains a topic for further research.

It is believed that invasive plant control has a greater chance of success when several methods of management are used in combination with each other (DiTomaso 2000). Although integrated management has been successful in controlling invasive forbs in many studies (Enloe and DiTomaso 1999; Jacobs et al. 2006; Jacobs and Sheley 1999; Radosevich et al. 2007; Renz and DiTomaso 1999), our results indicate that the integration of methods did not improve tall buttercup control. Only individual treatments provided control of tall buttercup; however, we were only able to test single application rates and timings for a short period of time. Despite our findings, it might still be beneficial to utilize an integrated approach when managing tall buttercup in North America given its history of evolved resistance to herbicides in New Zealand (Lamoureaux and Bourdôt 2007).

Prior to this study, little was known about how to successfully control tall buttercup in western North America. Our results indicate that the use of AMP, AMCP+CHL, and DIC provide at least short-term (up to 2 yr) control of tall buttercup infestations in hayfield meadows. Different application rates and timings of a variety of herbicides should be tested. For example, chemical control might be just as effective with less impact to nontarget species when implemented during late summer/early fall or in early spring prior to tall buttercup flowering (C. Duncan, personal communication, 2014). Our results indicate that mowing and fertilization might have potential for tall buttercup control, especially in subirrigated meadows, but both methods need further research. It is also important to consider that irrigation has been strongly linked to tall buttercup abundance (Bourdôt et al. 2013). Future research could test the use of grazing, mowing, fertilization, and herbicides in combination with each other and under various controlled irrigation schedules to examine their collective effects on tall buttercup abundance.

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