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Evaluation of Commercially Available Herbicide Mixes for Control of Rosette Stage Yellow Starthistle (*Centaurea solstitialis* L.)

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PURPOSE: Yellow starthistle is one of most problematic invasive species in grass and rangelands in the western United States. It has expanded its distribution since the 1950's threatening native species' diversity and reducing the utility of rangelands for livestock. Control of yellow starthistle has relied heavily on the use of picloram and clopyralid. Although these herbicides have been widely used and provide excellent control both pre-and post-emergence, new herbicide options need to be identified for rotation in herbicide stewardship programs. This study evaluated commercially available herbicide mixes as well as some herbicides that typically are not used in management programs to control mature plants just prior to the bolting growth stage.

INTRODUCTION: Yellow starthistle is one of the most widely distributed noncrop weeds found in rangeland, grassland, and wildland areas of the western United States, particularly California (DiTomaso et al. 2006a; Enloe et al. 2005). As of 2006, it is believed to have spread to over 15 million acres in California alone (DiTomaso et al. 2006a). Yellow starthistle induces fatal neurological diseases in horses, impacts and impairs training exercises, and damages equipment on military bases such as Ft Hunter Ligget, CA (FHL), and has directly resulted in millions of dollars in lost water for wildlife, agriculture, and municipal uses (Cordy 1978, DiTomaso et al. 2006a, Gerlach 2004).

Similar to winter annual grasses, yellow starthistle seeds rapidly germinate after the first autumn rains and continue to germinate as long as adequate moisture is present (Benefield et al. 2001, Maddox 1981, Roché et al. 1997). During winter, seedlings form rosettes and develop a deep taproot by early spring (DiTomaso et al. 2003). In late spring, plants bolt, followed by flowering and seed production during the summer and early fall, well after annual grasses have senesced (DiTomaso et al. 2003).

Burning, cultivation, mowing, timed grazing, biological controls, and herbicides have been utilized in attempts to control yellow starthistle (Eagle et al. 2007). Integrated approaches such as prescribed burning followed by herbicide treatment and native grass revegetation have shown promise (DiTomaso et al. 2006b, Enloe et al. 2005). However, these approaches may only be feasible on smaller infestations, largely dependent upon resources and labor for replanting of natives, or burning permit requirements. Therefore, herbicides are currently considered the most economical and effective method of controlling yellow starthistle (DiTomaso et al. 2006a). Several herbicides are effective for controlling yellow starthistle including picloram, clopyralid, triclopyr, dicamba 2,4-D, and metsulfuron (Northam and Callihan 1989, 1991). The objective of this research was to evaluate commercially available formulated mixes against yellow starthistle at the rosette growth stage, and compare these formulated mixes to herbicides traditionally used alone for yellow starthistle management.

MATERIALS AND METHODS: Yellow starthistle seed was collected at FHL in September 2007 and remained in cold storage until use. Approximately 300 seeds were planted on January 30, 2009 in three 26.7-by 53.3-cm (1423.1-cm^2) plastic planting flats amended with Jiffy Mix Premium Seed Starting Soil (Lorain, OH) in a greenhouse at the US Army Engineer Research and Development Center (USAERDC). The soil was watered daily (tap water) throughout seed germination until seedling transplant. The seedlings (ca. 3 cm in height) were transplanted, one seedling per pot, into 4-L (17-by 18-cm) pots containing Miracle-Gro® Potting Mix (Marysville, OH) on January 27, 2009. Plants were watered as needed and amended with Miracle-Gro® (36-6-6) fertilizer (Marysville, OH) every three weeks. The plants were treated with herbicide on April 10, 2009 just prior to reaching the bolting stage.

Herbicide treatments included: 2,4-D+triclopyr, picloram+2,4-D, aminopyralid+2,4-D, imazapic+glyphosate, aminopyralid, aminopyralid+triclopyr, diflufenzopyr+dicamba, imazamox, triclopyr+clopyralid, picloram+fluroxypyr, fluroxypyr, and dicamba+2,4-D. For a complete description of rates and commercially available herbicide mixes see Table 1. All herbicides were applied as a foliar treatment using a forced air CO_2-powered sprayer at an equivalent of 187 L/ha delivered through a single TeeJet® (Wheaton, IL) 80-0067 nozzle at 20 psi. A non-ionic surfactant was added to all spray materials at a rate of 0.25% v/v.

Yellow starthistle was assigned a phytotoxicity score at 17 days after treatment (DAT) to give an early indication of herbicide symptomology. Phytotoxicity scores are described in Nelson et al. (2001) and Robles et al. (2011). At 31 DAT, noticeably live plant material was harvested at the sediment surface, dried for 1 wk at 70 °C, and weighed to determine dry weight plant mass. Average pre-treatment biomass was 4.5±0.8 g and by 31 DAT reference plant biomass was 7.4±1.0 g (n=4), indicating plants were growing throughout the study. The treatments were randomly assigned and replicated four times. Statistical analyses were conducted using SAS® (Cary, NC). A mixed procedures model was utilized to examine herbicide effects on yellow starthistle biomass (Littell et al. 1996). If a significant herbicide effect was observed, treatment means were separated using least squares means and grouped using the least significant difference method. All analyses were conducted at a $p<0.05$ level of significance.

RESULTS AND DISCUSSION: Most herbicides and herbicide combinations evaluated in this study resulted in severe injury to yellow starthistle by 17 DAT, where phytotoxicity scores ranged from 7 to 9; with the exception of imazamox and imazapic+glyphosate treatments (Table 1). Yellow starthistle treated with imazamox and imazapic+glyphosate resulted in mild to severe phytotoxicity scores relative to untreated reference plants at 17 DAT (Table 1). Imazamox treatments included symptomatic chlorosis and witches broom, yet these symptoms did not result in plant death. Witches broom is common when apical meristems are injured or exposed to ALS herbicide applications (Shaner 1991).

The commercially available herbicide mix of imazapic+glyphosate had variable phytotoxic symptoms where the rates of 26.3+52.6 and 105.3+210.7 g ae/ha resulted in severe damage to treated plants (Table 1); though this herbicide mix did not result in biomass reductions in yellow

Table 1. Phytotoxicity ratings of yellow starthistle treated at the rosette growth stage with select herbicides at 17 days after treatment (n=4).

Treatment	Tradename	Rate (g ae/ha)	Phytotoxicity Ratings[1]
Untreated Reference		0	1
2,4-D+triclopyr	Crossbow™	280.9 + 140.4 561.8 + 280.9 1123.7 + 561.8 1685.6 + 1123.7	9 9 9 9
Picloram+2,4-D	Grazon P+D®	37.9 + 140.4 75.8 + 280.9 151.7 + 561.8 303.4 + 1123.7	8 8 9 9
Aminopyralid+2,4-D	GrazonNext™	34.7 + 281.2 69.5 + 562.5 86.9 + 703.2 104.2 + 843.8	9 9 9 9
Imazapic+glyphosate	Journey®	13.1 + 26.3 26.3 + 52.6 52.6 + 105.3 105.3 + 210.7	5 8 3 7
Aminopyralid	Milestone®	26.3 52.6 70.2 105.3	7 9 9 9
Aminopyralid+triclopyr	Milestone® VM Plus	28.1 + 280.9 56.1 + 561.8 84.2 + 842.8 112.3 + 1123.7	9 9 9 9
Diflufenzopyr+dicamba	Overdrive®	28.1 + 70.2 56.1 + 140.4 84.2 + 210.7 112.3 + 280.9	8 8 9 8
Imazamox	Raptor®	17.5 26.3 35.1 43.8	5 2 4 4
Triclopyr+clopyralid	Redeem R+P®	158.0 + 52.6 316.1 + 105.3 632.1 + 210.7 948.1 + 316.1	9 9 9 9
Picloram+fluroxypyr	Surmount®	70.5 + 70.5 141.1 + 141.1 282.3 + 282.3 364.6 + 364.6	7 9 9 9
Fluroxypyr	Vista®	69.1 138.2 276.5 421.4	7 9 8 9
Dicamba+2,4-D	Weedmaster®	70.2 + 201.5 140.4 + 403.1 280.9 + 806.2 561.8 + 1612.5	8 9 9 9

[1] 1-No visible effect; green, healthy tissues; no herbicide damage; identical to untreated reference
2-Very mild symptoms; slight color change (mild yellowing or browning); plants will recover
3-Mild symptoms; off-color plant tissues; more severe discoloration than #2 rating
4-Clear symptoms; probably won't result in plant death
5- Clear symptoms; possible permanent damage to plant tissues
6- Distinct damage on 25% of plant tissues (but less than 50%)
7- Severe damage on 50% of plant tissues (but less than 75%)
8-Very severe damage; 75% of tissues affected (but less than 100%)
9- Necrotic, collapsing tissues; damage on 100% of plants; total destruction of plant stand

starthistle like other commercially available herbicide mixes (Table 2). The poor efficacy with imazapic+glyphosate was somewhat surprising as glyphosate applied alone has been reported to be very efficacious against yellow starthistle in late season applications (DiTomaso et al. 1999, 2006a). The reduced efficacy with imazapic+glyphosate could be attributed to herbicide movement to the apical structures during the bolting stage and not downward to underground structures, thereby limiting systemic efficacy.

Table 2. Mean (± 1 SE) yellow starthistle biomass at 31 days after treatment with select herbicides. Yellow starthistle was treated at the rosette growth (bolting) stage.

Treatment	Tradename	Rate (g ae/ha)	Biomass (g)[1]	Biomass Reduction (%)
Untreated Reference		0	7.4 ± 0.9 a	
2,4-D + triclopyr	Crossbow™	280.9 + 140.4	0.1 ± 0.1 i	99
		561.8 + 280.9	0.3 ± 0.3 hi	96
		1123.7 + 561.8	0.4 ± 0.4 hi	95
		1685.6 + 1123.7	0 ± 0 i	100
Picloram + 2,4-D	Grazon P+D®	37.9 + 140.4	0.9 ± 0.4 hi	87
		75.8 + 280.9	1.9 ± 0.3 fghi	74
		151.7 + 561.8	0.3 ± 0.3 hi	96
		303.4 + 1123.7	0.4 ± 0.4 hi	95
Aminopyralid + 2,4-D	GrazonNext™	34.7 + 281.2	0 ± 0 i	100
		69.5 + 562.5	0 ± 0 i	100
		86.9 + 703.2	0 ± 0 i	100
		104.2 + 843.8	0 ± 0 i	100
Imazapic + glyphosate	Journey®	13.1 + 26.3	8.2 ± 1.9 a	0
		26.3 + 52.6	3.4 ± 1.7 def	54
		52.6 + 105.3	7.2 ± 1.1 a	3
		105.3 + 210.7	4.2 ± 1.7 cde	43
Aminopyralid	Milestone®	26.3	3.5 ± 1.1 def	53
		52.6	0 ± 0 i	100
		70.2	0 ± 0 i	100
		105.3	0.4 ± 0.4 hi	95
Aminopyralid + triclopyr	Milestone® VM Plus	28.1 + 280.9	0 ± 0 i	100
		56.1 + 561.8	0 ± 0 i	100
		84.2 + 842.8	0 ± 0 i	100
		112.3 + 1123.7	0 ± 0 i	100
Diflufenzopyr + dicamba	Overdrive®	28.1 + 70.2	3.2 ± 2.0 defg	57
		56.1 + 140.4	1.7 ± 0.9 fghi	77
		84.2 + 210.7	0.4 ± 0.2 hi	95
		112.3 + 280.9	1.0 ± 0.3 ghi	86
Imazamox	Raptor®	17.5	4.8 ± 2.1 bcd	35
		26.3	6.2 ± 0.3 abc	16
		35.1	7.0 ± 1.4 ab	5
		43.8	6.2 ± 1.0 abc	16
Triclopyr + clopyralid	Redeem R+P®	158.0 + 52.6	0 ± 0 i	100
		316.1 + 105.3	0.1 ± 0.1 i	99
		632.1 + 210.7	0 ± 0 i	100
		948.1 + 316.1	0 ± 0 i	100
Picloram + fluroxypyr	Surmount®	70.5 + 70.5	2.5 ± 1.1 efgh	66
		141.1 + 141.1	0 ± 0 i	100
		282.3 + 282.3	0.6 ± 0.6 hi	92
		364.6 + 364.6	0 ± 0 i	100
Fluroxypyr	Vista®	69.1	1.7 ± 0.7 fghi	77
		138.2	1.1 ± 1.1 ghi	85
		276.5	1.4 ± 0.6 fghi	81
		421.4	0.1 ± 0.1 i	99
Dicamba + 2,4-D	Weedmaster®	70.2 + 201.5	1.5 ± 0.5 fghi	80
		140.4 + 403.1	0 ± 0 i	100
		280.9 + 806.2	0 ± 0 i	100
		561.8 + 1612.5	0 ± 0 i	100

[1] Means in a column followed by the same letter are not statistically different according to the LSD procedure at a $p<0.05$ level of significance.

Herbicide treatments that included aminopyralid resulted in 95 to 100 percent biomass reduction with the exception of aminopyralid applied at 26.3 g ae/ha (53 percent biomass reduction). When aminopyralid was combined with either 2,4-D or triclopyr and applied below the recommended rate, it resulted in excellent yellow starthistle control (Table 2). Aminopyralid has a similar mode of action to clopyralid, though yellow starthistle can be effectively controlled with aminopyralid using herbicide rates about half that of clopyralid (DiTomaso et al. 2006a). The combinations of aminopyralid with 2,4-D or triclopyr could also allow flexibility in treatment timing because aminopyralid could provide pre-emergence control while the 2,4-D and triclopyr would control those plants that have already germinated. Soil residual time would depend upon application rates; therefore, if pre-emergence control was desired, the lower use rates may not be as effective. Aminopyralid generally has a longer soil residual than clopyralid, though somewhat less selectivity (DiTomaso et al. 2006a). More research is required to test the feasibility and potential success of these new treatment strategies.

The commercially available herbicide mix of triclopyr+clorpyralid was tested because the efficacy and use patterns of clopyralid used alone is well documented (DiTomaso et al.1999, 2006a, 2006b; Enloe et al. 2005). The efficacy of triclopyr+clorpyralid on yellow starthistle was similar to that of aminopyralid+triclopyr and aminorpyralid+2,4-D where 99- to 100-percent reductions were observed in yellow starthistle biomass (Table 2). One advantage of using clopyralid over aminopyralid would be increased selectivity on grasses and most broadleaf species (DiTomaso et al.1999, 2006a); though clopyralid is generally slower acting than other growth regulating herbicides (DiTomaso et al. 2006a). However, the combination of triclopyr with clopyralid may reduce the amount of time and herbicide rate necessary to achieve similar control when clopyralid is used alone. As with previously discussed results, more research is necessary to test these potential treatment strategies.

Outside of California, where clopyralid is predominately used, picloram has been the most effective and frequently used herbicide for yellow starthistle control (DiTomaso et al. 2006a, Miller et al. 2001). In the current study, commercially available herbicide mixes of picloram were evaluated including picloram+2,4-D and picloram+fluroxypyr. Overall, the reduction of yellow starthistle biomass using these commercially available herbicide mixes was similar to that of the aminopyralid and clopyralid mixes with the exception of picloram+fluroxypyr applied at 70.5+70.5 g ae/ha (66-percent biomass reduction). The lower rates of picloram+2,4-D offered 74- to 87-percent biomass reduction, whereas the higher rates resulted in >95-percent biomass reduction. There was no significant improvement in control by combining picloram with fluroxypyr versus fluroxypyr alone. Under field situations, however, the addition of picloram will offer soil residual and pre-emergence control that fluroxypyr alone will not. The use of picloram can provide two to three years of yellow starthistle control (Northam and Callihan 1989); though picloram is often less selective than other herbicides such as clopyralid and aminopyralid (DiTomaso et al. 2006a).

Other commercially available herbicide mixes evaluated were 2,4-D+triclopyr, diflufenzopyr+dicamba, and dicamba+2,4-D, all of which performed similar to previously described commercial mixes, with the exception of some of the lower herbicide rates tested. Overall, these commercially available herbicide mixes provided between 80- and 100-percent biomass reductions, except for the lowest difluenzopyr+dicamba rate tested, which resulted in only 57-percent biomass reduction. A potential disadvantage of these formulated mixes with respect to yellow starthistle management is they do not offer the flexibility or added efficacy of pre-emergence control since these herbicides do not have soil activity and can only be applied post emergence. Yellow starthistle seeds begin to germinate in autumn when rain returns to the western United States (Benefield et al. 2001, Roché et al. 1997), and will continue to germinate through winter and spring as long adequate moisture is present (Callihan et al. 1990, DiTomaso et al.1999). This prolonged germination time results in several applications of post-emergence herbicides to gain control of yellow starthistle populations (DiTomaso et al.1999). However, pre-emergent herbicides could control plants during the extended germination period, reducing the number of treatments necessary to control yellow starthistle.

Overall, the herbicides tested alone and as commercially available herbicide mixes resulted in similar yellow starthistle control with the exception of imazamox and imzapic+glyphosate. These data provide evidence of additional products that could be effective and utilized in yellow starthistle management programs. These results also demonstrate that plants in the rosette stage can be controlled using foliar applications at reduced herbicide rates. Additional flexibility in application timings may be gained especially when considering the soil residual times of clopyralid, aminopyralid, and picloram. Herbicide selection, whether chemistries are applied alone or in commercially available herbicide mixes, will ultimately be decided upon by cost, species selectivity, availability, and whether or not states allow their use. The majority of herbicides already utilized for yellow starthistle control and many tested in this study are auxinic growth-regulating herbicides. A picloram-resistant population of yellow starthistle already exists in the state of Washington (Callihan et al. 1990). This population may also have cross resistance to clopyralid, dicamba, 2,4-D, and fluroxypyr (Fuerst et al. 1996, Miller et al. 2001). If this population escapes its current location or new resistant populations emerge, it could be disastrous for weed management programs in the western United States due to increased management costs and a decrease in the amount of managed acres, ultimately resulting in reduced quality and use of rangelands by livestock. Additional research is needed to identify different modes of action that are efficacious against yellow starthistle, new integrated approaches to yellow starthistle management, and the feasibility of implementing integrated approaches on large scales.

FUTURE WORK: This research should be verified in the field to demonstrate the efficacy of the newer products and herbicide tank mixes to control yellow starthistle. In addition, other commercially available herbicide mixes and recently registered herbicides should be evaluated in greenhouse trials.

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