Research Reports

Creeping Bellflower Response to Glyphosate and Synthetic Auxin Herbicides

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Summary. Creeping bellflower (*Campanula rapunculoides*) is a difficult to manage weed commonly found in turfgrass and residential areas. We evaluated the efficacy of selected postemergence herbicides (glyphosate, dicamba, clopyralid, quinclorac, and triclopyr) on greenhouse-grown creeping bellflower. The experiment was conducted in Jan. 2016 and repeated in Sept. 2016. Each herbicide was applied at five rates plus a nontreated control. Clopyralid caused greater creeping bellflower biomass reduction and mortality than the other herbicides investigated. The herbicide dose required to cause 50% mortality was lowest for clopyralid [86–138 g·ha^{-1} acid equivalent (a.e.)] compared with dicamba (221–536 g·ha^{-1} a.e.), glyphosate (196–678 g·ha^{-1} a.e.), triclopyr (236–782 g·ha^{-1} a.e.), and quinclorac (>3000 g·ha^{-1} a.e.). Clopyralid could be an effective herbicide for managing creeping bellflower, although it is currently not registered for use in many habitats where this plant is a problematic weed.

The genus *Campanula* is composed of a diverse group of perennial, biennial, and annual species that are distributed across temperate and higher elevation subtropical regions (Rosatti, 1986). A limited number of bellflower (*Campanula*) species are cultivated for their attractive bell-shaped flowers that have a variety of ornamental uses (Seglie et al., 2012). Creeping bellflower is a creeping perennial native to Eurasia that is widely naturalized in North America growing in turfgrass, gardens, roadsides, and wooded areas (Rosatti, 1986; U.S. Department of Agriculture, 2017). Many of the same traits that make it a desirable, low-maintenance ornamental plant make it a vigorous weed problem once it escapes cultivation (Whitson, 2012). This rhizomatous, low-growing herb has heart-shaped, toothed leaves that produce flowering racemes, each containing from 20 to 100 flowers (Good-Avila and Stephenson, 2003; Vogler and Stephenson, 2001). Racemes can produce 3000 to 15,000 seeds annually (Royer and Dickinson, 1999) with subsequent germination rates greater than 60% (Good-Avila and Stephenson, 2003).

Creeping bellflower has long been considered an aggressive turfgrass and pasture weed in the United States (Stevens, 1966), but the relative contribution of sexual and asexual reproduction to this species' competitiveness is unknown. The floral reproductive biology of creeping bellflower is well studied because of transient self-incompatibility in which the stigmas of the flowers exhibit plastic incompatibility that changes over time (Vogler and Stephenson, 2001). Levels of self-incompatibility are influenced by genetic and environmental factors that result in variable self-fertilization rates in natural populations (Good-Avila et al., 2003). The contribution of seed production and vegetative growth to this species' success is thus likely influenced by access to suitable pollen and environmental factors. Asexual reproduction may play an important role in turfgrass or hayfields that receive frequent mowing whereas plants growing in undisturbed areas may exhibit varying degrees of sexual and asexual reproduction.

Herbicides are important tools for weed control in turfgrass and other areas and can be particularly effective when used in combination with cultural and mechanical control practices (DiTomaso, 2000; Grube et al., 2011). Of the herbicides labeled for weed control in turfgrass and residential areas, synthetic auxins and glyphosate are used most frequently (Grube et al., 2011). Numerous extension bulletins in the United States provide general recommendations for chemical control of creeping bellflower but only a few contain herbicide efficacy information (Callihan and Old, 1990; Moechnig et al., 2007; Panke et al., 2012). Where

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.0731	fl oz/acre	L·ha^{-1}	13.6840
0.3048	ft	m	3.2808
3.7854	gal	L	0.2642
9.3540	gal/acre	L·ha^{-1}	0.1069
2.54	inch(es)	cm	0.3937
1.1209	lb/acre	kg·ha^{-1}	0.8922
119.8264	lb/gal	g·L^{-1}	0.0083
70.0532	oz/acre	g·ha^{-1}	0.0143
(°F – 32) ÷ 1.8	°F	°C	(°C × 1.8) + 32

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Table 1. Herbicide rates and adjuvants applied to creeping bellflower.

Herbicide	Rates (g·ha^{-1} a.e.)[z]						Adjuvant(s)[y]
Glyphosate	0	280	561	1,120	2,240	4,480	AMS (20 g·L^{-1})
Dicamba	0	70	140	280	560	1,120	UAN 28-0-0 (4.68 L·ha^{-1}) NIS (0.25% v/v)
Clopyralid (Expt. 1)	0	110	210	420	840	1,680	
Clopyralid (Expt. 2)	0	13	26	53	105	420	
Quinclorac (Expt. 1)	0	210	420	840	1,680	3,360	COC (2.34 L·ha^{-1})
Quinclorac (Expt. 2)	0	420	840	1,640	3,360	6,730	COC (2.34 L·ha^{-1})
Triclopyr	0	210	420	840	1,680	3,360	NIS (0.25% v/v)

[z]Rates expressed in acid equivalent (a.e.); 1 g·ha^{-1} = 0.0143 oz/acre.
[y]AMS = ammonium sulfate (N Pak AMS liquid; WinField Solutions, St. Paul, MN); UAN = urea ammonium nitrate (UAN 28-0-0; Agrium, Calgary, Canada); NIS = nonionic surfactant (Preference, WinField Solutions); COC = crop oil concentrate (Prime Oil, WinField Solutions); 1 g·L^{-1} = 0.0083 lb/gal; 1 L·ha^{-1} = 0.1069 gal/acre.

Table 2. Herbicide doses required to cause 50% mortality (LD_{50}) and 50% dry matter reduction (GR_{50}) in creeping bellflower under greenhouse conditions.

		LD_{50}	(SE)	GR_{50}	(SE)
Expt. no.	Herbicide	(g·ha^{-1} a.e.)[z]			
1	Clopyralid	138	(37)	28	(208)
1	Dicamba	536	(134)	76	(18)
1	Glyphosate	678	(167)	251	(54)
1	Triclopyr	782	(191)	203	(51)
1	Quinclorac	>3,360[y]	—	1,002	(500)
2	Clopyralid	86	(29)	25	(14)
2	Dicamba	221	(69)	146	(32)
2	Glyphosate	196	(89)	137	(623)
2	Triclopyr	236	(88)	89	(117)
2	Quinclorac	3,450	(1,132)	832	(73)

[z]Rates expressed in acid equivalent (a.e.); 1 g·ha^{-1} = 0.0143 oz/acre.
[y]LD_{50} and SE values could not be estimated for quinclorac from Expt. 1 because no mortality was observed even at the highest quinclorac rate (3,360 g·ha^{-1} a.e.).

efficacy information is included, there is some inconsistency among publications, and in all cases, it is unclear if recommendations are based on experimental data, personal experience, or general knowledge of herbicide chemistry. For example, Panke et al. (2012) report that labeled rates of dicamba or picloram can provide control of creeping bellflower, but Moechnig et al. (2007) report that commercially available synthetic auxin herbicides only provide suppression. Considering the widespread distribution and creeping growth habit, selective herbicides need to be identified that minimize regrowth and vegetative spread. The objective of this study was to examine the efficacy of glyphosate and synthetic auxin herbicides on greenhouse-grown creeping bellflower.

Materials and methods

Greenhouse studies were conducted in 2016 at the University of Wyoming Laramie Research and Extension Center, Laramie, to evaluate the efficacy of selected herbicides on creeping bellflower. In May 2015, ≈1 m of creeping bellflower rhizome was dug from a large infestation in the corresponding author's front lawn in Laramie, WY. Rhizome segments were planted into twenty 2-L pots filled with potting medium (BM Custom Blend; Berger, Saint-Modeste, QC, Canada) and placed in the greenhouse to increase root and rhizome biomass for 8 months. Rhizomes were then dug from the large pots, and cut into 8-cm segments and planted on 5 Jan. 2016 (Expt. 1). Remaining rhizomes were replanted into 2-L pots again and allowed to continue growing until the process was repeated on 15 Sept. 2016 (Expt. 2). For both experiments, the rhizomes were planted into 0.9-L pots filled with potting medium (BM Custom Blend) and watered twice daily. No fertilizer was applied. Day and night temperatures were maintained at 22 and 20 °C, respectively. A supplemental light (Sun System; Sunlight Supply, Vancouver, WA) was used to extend the photoperiod (16 h light and 8 h dark) throughout the experiments.

In both experiments, five different rates of glyphosate (Roundup Weathermax; Monsanto Company, St. Louis, MO), dicamba (Clarity; BASF Corp., Durham, NC), clopyralid (Stinger; Dow AgroSciences, Indianapolis, IN), quinclorac (Facet L and Facet 75 DF, BASF Corp.), and triclopyr (Garlon 3A, Dow AgroSciences) were used (Table 1). Each herbicide was applied with the label recommended adjuvant (Table 1). A nontreated control was also included (Table 1). Because of the high efficacy of clopyralid and low efficacy of quinclorac in Expt. 1, rates of clopyralid were reduced and rates of quinclorac increased in Expt. 2. In addition, a liquid formulation of quinclorac (Facet L) was used in Expt. 2 instead of the dry formulation (Facet 75 DF) used in Expt. 1. Each herbicide rate was replicated five times in a completely randomized design in each study. Plants were treated at an average height of 5 cm, which corresponded to 23 and 20 d after planting in Expts. 1 and 2, respectively. Treatments were applied when plants were 5 cm in height to simulate plants growing in mowed turfgrass.

Aboveground biomass was clipped 7 and 8 d after treatment in Expts. 1 and 2, respectively. Regrowth of creeping bellflower plants was evaluated 14 d after top growth removal. Regrowth was recorded as a binary variable by assigning 0 if no leaf was visible and 1 if at least one leaf was present. Aboveground biomass was clipped again 16 and 21 d after the first clipping in Expts. 1 and 2, respectively. Aboveground biomass from the final clipping was oven-dried at 60 °C for 48 h and weighed.

Nonlinear regression analysis was used to quantify the effect of each herbicide on creeping bellflower dry matter production after clipping and probability of regrowth after clipping. For dry matter production, a three-parameter log-logistic model was used (Eq. [1]), where Υ is dry matter

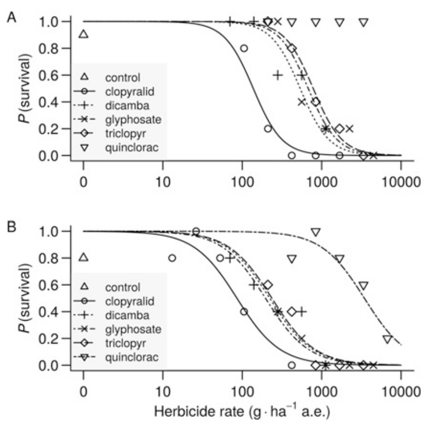

Fig. 1. Probability of creeping bellflower survival after treatment with five different herbicides under greenhouse conditions in two experiments. (A) Plants sprayed in Jan. 2016 and survival (regrowth) assessed 19 d after treatment. (B) Plants sprayed in Sept. 2016 and survival (regrowth) assessed 32 d after treatment. Rates expressed in acid equivalent (a.e.); 1 g·ha^{-1} = 0.0143 oz/acre.

of aboveground biomass regrowth in grams, *d* is the upper limit asymptote, *X* is the rate of the herbicide applied in grams acid equivalent per hectare, *e* is the value of *X* at the inflection point of the curve, and *b* is the slope of the curve at *e* (Seefeldt et al., 1995).

$$Y = d\Big/\left(1 + (X/e)^{b}\right) \qquad [1]$$

For the dry matter analysis, the model parameters in Eq. [1] have practical interpretations: *d* is an estimate of the dry matter production when no herbicide is applied (similar to the y-intercept in linear regression) and *e* is an estimate of the herbicide rate required to cause a 50% dry matter growth reduction (GR_{50}). For the binomial variable of regrowth (a proxy for plant survival after clipping), the *d* parameter in Eq. [1] was fixed at 1, which results in a two-parameter log-logistic model, where *e* and *b* retain the same interpretation as previously mentioned so that *e* is an estimate of the herbicide rate required to cause 50% mortality (LD_{50}). Also, the herbicide rate required for 90% mortality (LD_{90}) was estimated. Nonlinear regression analysis was conducted in the R statistical language using the drc package (R Core Team, 2016; Ritz and Streibig, 2005).

Table 3. Herbicide doses required to cause 90% control (LD_{90}) of creeping bellflower under greenhouse conditions and the recommended rate on herbicide label for perennial weed control.

Trade name	Active ingredient	Estimated LD_{90} (fl oz/acre)[z]	Recommended rate for perennial weed control
Stinger (Dow AgroSciences)	Clopyralid	12.8–13.2	5.3–21.3
Clarity (BASF Corp.)	Dicamba	25–38.4	8–32
Roundup WeatherMax (Monsanto)	Glyphosate	19.6–42.7	12.8–105.6
Garlon 3A (Dow AgroSciences)	Triclopyr	35.4–72.5	32–384
Facet L (BASF Corp.)	Quinclorac	≥1,024	22–64

[z]Rates expressed are of commercial formulation; 1 fl oz/acre = 0.0731 L·ha^{-1}.

Results and discussion

Creeping bellflower was effectively controlled under greenhouse conditions at high rates of all herbicides evaluated except for quinclorac. Quinclorac was not effective for creeping bellflower control, although the increased dose improved suppression in Expt. 2 (Table 2). Herbicide LD_{50} and GR_{50} were generally less in Expt. 2, as were the estimated standard errors. The greater LD_{50} and GR_{50} estimates observed in Expt. 1 could be due to reduced light quantity and quality when the experiment was conducted (January for Expt. 1 vs. September for Expt. 2). In both experiments, LD_{50} estimates were greater than GR_{50} estimates, with GR_{50} estimates often less than half the LD_{50} estimates. This is expected, because a greater amount of herbicide is required to kill plants than to reduce growth.

Clopyralid was the most effective herbicide tested as evidenced by the lowest LD_{50} and GR_{50} in both experiments (Table 2; Fig. 1). Estimated LD_{90} of clopyralid was within the recommended rate range for perennial weed control (Table 3). In Expt. 1, clopyralid LD_{50} values were 74% to 82% less than dicamba, glyphosate, and triclopyr. Reducing the clopyralid doses in Expt. 2 resulted in a better characterization of creeping bellflower response, which resulted in more accurate estimates of LD_{50} and GR_{50}. Clopyralid LD_{50} values were 56% to 64% lower than dicamba, glyphosate, and triclopyr in the second study.

Moechnig et al. (2007) reported that triclopyr provides suppression of creeping bellflower but not effective control. Although triclopyr resulted in injury symptoms such as curled leaves and generally lower rates were required to reduce growth (GR_{50}), greater rates were required to cause mortality compared with dicamba, glyphosate, or clopyralid (Table 2). Although LD_{90} estimates of triclopyr were within the range of recommended rates for perennial weed control (Table 3), the range of recommended rates is extremely wide because triclopyr is commonly used for woody shrub control. Thus, triclopyr might not be practical for controlling creeping bellflower in turfgrass, where recommended broadcast rates typically range from 0.5 to 1 lb/acre.

Glyphosate and dicamba are often reported as options for chemical control of creeping bellflower (Panke et al., 2012; Whitson, 2003; Wisconsin Department of Natural Resources, 2009, 2012). For example, Panke et al. (2012) report that labeled rates of glyphosate or dicamba can provide 70% to 90% control of creeping bellflower. Moechnig et al. (2007) stated that an herbicide that contains dicamba can suppress creeping bellflower, but repeated applications may be necessary for effective control. Estimated LD_{90} of dicamba was outside the range of recommended rates for perennial weed control (Table 3). Thus, field use rates of dicamba may not provide good control (≥90%) of creeping bellflower. As observed with triclopyr, dicamba application may allow resprouting after clipping, necessitating reapplication. Repeated applications may, however, improve creeping bellflower control by dicamba

(Moechnig et al., 2007). In our experiments, glyphosate LD_{50} was more than three times greater in Expt. 1 than Expt. 2, but overall creeping bellflower would have been controlled (≥90% control) by glyphosate at field use rates (Table 3). However, greenhouse results are not always indicative of rates required to control weeds in the field. Masengarb (1999) reported that repeated applications of glyphosate may be needed to control creeping bellflower.

We acknowledge the limitations of this greenhouse research, because field results sometimes differ, especially with respect to the herbicide rates required to control a species. However, relative ranking between herbicides with respect to weed control efficacy tend to be similar between field and greenhouse studies. Although we did not evaluate the efficacy of mixtures of two or more active ingredients in this study, it is possible that mixtures could provide improved control of creeping bellflower. Testing the efficacy of active ingredient mixtures is particularly important in turfgrass weed management because products for turfgrass weed control are often a combination of several active ingredients (Raudenbush and Keeley, 2014). Future research should evaluate the efficacy of mixtures on field populations, especially those that have shown promising results in this study. In addition, evaluating the efficacy of these herbicides at different growth stages of creeping bellflower will be important for determining the optimal application timing. Clopyralid was consistently the most effective herbicide for controlling creeping bellflower and displays similar grass selectivity as other synthetic auxins such as dicamba and triclopyr. Despite selectivity and labeled use in permanent grass pastures, grasses grown for seed, turfgrass in specific areas, and noncropland, clopyralid is not currently labeled for use in other areas where creeping bellflower is commonly found, such as residential areas.

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