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Response of Palmer amaranth (*Amaranthus palmeri* S. Watson) and sugarbeet to desmedipham and phenmedipham

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Abstract

A prepackaged mixture of desmedipham + phenmedipham was previously labeled for control of *Amaranthus* spp. in sugarbeet. Currently, there are no effective POST herbicide options to control glyphosate-resistant Palmer amaranth in sugarbeet. Sugarbeet growers are interested in using desmedipham + phenmedipham to control escaped Palmer amaranth. In 2019, a greenhouse experiment was initiated near Scottsbluff, NE, to determine the selectivity of desmedipham and phenmedipham between Palmer amaranth and sugarbeet. Three populations of Palmer amaranth and four sugarbeet hybrids were evaluated. Herbicide treatments consisted of desmedipham and phenmedipham applied singly or as mixtures at an equivalent rate. Herbicides were applied when Palmer amaranth and sugarbeet were at the cotyledon stage, or two true-leaf sugarbeet stage and when Palmer amaranth was 7 cm tall. The selectivity indices for desmedipham, phenmedipham, and desmedipham + phenmedipham were 1.61, 2.47, and 3.05, respectively, at the cotyledon stage. At the two true-leaf application stage, the highest rates of desmedipham and phenmedipham were associated with low mortality rates in sugarbeet, resulting in a failed response of death. The highest rates of desmedipham + phenmedipham caused a death response of sugarbeet; the selectivity index was 2.15. Desmedipham treatments resulted in lower LD_{50} estimates for Palmer amaranth compared to phenmedipham, indicating that desmedipham can provide greater levels of control for Palmer amaranth. However, desmedipham also caused greater injury in sugarbeet, producing lower LD_{50} estimates compared to phenmedipham. Desmedipham + phenmedipham provided 90% or greater control of cotyledon-size Palmer amaranth at a labeled rate but also caused high levels of sugarbeet injury. Neither desmedipham, phenmedipham, nor desmedipham + phenmedipham was able to control 7-cm tall Palmer amaranth at previously labeled rates. Results indicate that desmedipham + phenmedipham can only control Palmer amaranth if applied at the cotyledon stage and a high level of sugarbeet injury is acceptable.

Introduction

Sugarbeet is considered a poor competitor with weeds, compared to corn (*Zea mays* L.) and soybean (*Glycine max* L. Merr.), due to its low stature and relatively slow growth rate. Consequently, weed competition is considered one of the most limiting factors in sugarbeet production (Dawson 1965; Zimdahl and Fertig 1967). It is estimated that without effective weed control, sugarbeet yield in North America would be reduced by 70% (Soltani et al. 2018). By comparison, yield of corn and soybean would be expected to be reduced 50% without effective weed control (Soltani et al. 2016, 2017).

Desmedipham and phenmedipham are photosystem II inhibitors in the phenylcarbamate family (WSSA Site of Action Group 5). Desmedipham and phenmedipham were used extensively for POST weed control in sugarbeet before the development and commercial cultivation of glyphosate-resistant sugarbeet. These herbicides provide selective weed control because, compared to susceptible weed species, sugarbeet exhibits rapid metabolism of desmedipham and phenmedipham (Hendrick et al. 1974). Desmedipham, marketed as the product Betanex® (Bayer CropScience, Research Triangle Park, NC) (Anonymous 2010), was primarily used for control of redroot pigweed (*Amaranthus retroflexus* L.) (Eshel et al. 1976) because phenmedipham was not effective (Hendrick et al. 1974). A prepackaged mixture of desmedipham + phenmedipham became available in 1982 for POST weed control (Dexter 1994), registered as the product Betamix® (Bayer CropScience) (Anonymous 2011). U.S. registration for the products Betamix and Betanex was cancelled in 2014 (EPA 2014).

Desmedipham + phenmedipham effectively controls the annual broadleaf species redroot pigweed, common lambsquarters (*Chenopodium album* L.), and hairy nightshade (*Solanum sarrachoides* Sendtn.) (Anonymous 2011), while improving crop safety in comparison to POST application of desmedipham (Dexter 1994). However, even with improved crop safety of desmedipham + phenmedipham, application was known to cause injury in sugarbeet (Dexter 1994; Weinlaeder and Dexter 1972) and reduce yield (Starke et al. 1996; Wilson 1999).

A split-rate application program was developed in an effort to reduce sugarbeet injury, using a half rate of desmedipham + phenmedipham, followed by a second application 5–7 d later (Dexter 1994). The split-rate program provided greater control of redroot pigweed and reduced sugarbeet injury compared to applying a full rate of desmedipham + phenmedipham in a single POST application (Dexter 1994). The split-rate program was additionally modified into a "microrate" program, which involved the further lowering of herbicide rates to allow up to three sequential POST applications (Dale et al. 2006). The microrate program later included the herbicides ethofumesate, triflusulfuron, and clopyralid in addition to desmedipham + phenmedipham (Dale et al. 2006). The microrate program was widely used in sugarbeet production regions of North Dakota and Minnesota (Dexter and Luecke 1998).

Weed management was intensive with the aforementioned herbicides combined in a microrate program, and sugarbeet injury was expected even with multiple applications at regular intervals (Morishita 2017). Not surprisingly, adoption of glyphosate-resistant sugarbeet was rapid once it became commercially available in 2007 (Khan 2010; Morishita 2017). Glyphosate provided excellent control of annual broadleaf species in sugarbeet, such as kochia [*Bassia scoparia* (L.) A.J. Scott], common lambsquarters, and redroot pigweed (Knezevic et al. 2020). POST applications of glyphosate in glyphosate-resistant sugarbeet increased weed control, reduced crop injury, and presented cost savings compared with other herbicide options, including desmedipham + phenmedipham (Kniss et al. 2004; Morishita 2017; Wilson et al. 2002). Since the introduction of glyphosate-resistant sugarbeet, 99% of sugarbeet acreage in the United States is planted to glyphosate-resistant sugarbeet for weed control (Fernandez-Cornejo et al. 2016).

Glyphosate-resistant sugarbeet technology has been highly successful and, as a result, the Betamix and Betanex product registrations have expired, leaving only clopyralid, triflusulfuron, and glyphosate as registered POST broadleaf weed control products available in sugarbeet. Long-chain fatty acid–inhibiting herbicides (Group 15) are labeled for POST application in sugarbeet, but due to crop safety concerns, can only be applied after sugarbeet reaches two true leaves. Ethofumesate (Group 16) and cycloate (Group 8) are labeled for PRE application in sugarbeet but have little activity on *Amaranthus* spp. (Kniss and Lawrence 2020). There are no labeled herbicides that are available to control broadleaf weeds that emerge between planting and the two true leaf stage and that are resistant or have reduced susceptibility to glyphosate, triflusulfuron, and clopyralid.

Glyphosate-resistant Palmer amaranth is becoming widespread in the sugarbeet production regions of western Nebraska and eastern Colorado (Vieira et al. 2017). Palmer amaranth is a dioecious species, native to the southwestern United States and Mexico (Sauer 1957). It is particularly troublesome in crop production due to its ability to emerge for a long time during the growing season (Jha and Norsworthy 2009). Palmer amaranth achieves optimum germination at fluctuating soil temperatures above 20 C and emerges rapidly in comparison with other *Amaranthus* species (Steckel et al. 2004). Palmer amaranth is a highly competitive weed species because of its rapid rate of growth (Jha et al. 2008) and prolific seed production (Chahal et al. 2015; Ward et al. 2013). Palmer amaranth is resistant to glyphosate in many areas of the United States (Chahal et al. 2017; Culpepper et al. 2006; Vieira et al. 2017), which greatly compromises weed control in sugarbeet and threatens future production (Morishita 2017).

Multiple *Amaranthus* species have reduced sugarbeet root yield, including Powell amaranth (*A. powellii* S. Watson) (Schweizer and Lauridson 1985), Palmer amaranth (Schultz and Lawrence, 2019), and redroot pigweed (Brimhall et al. 1965; Heidari et al. 2007; Stebbing et al. 2000). Sugarbeet growers in western Nebraska and eastern Colorado are searching for alternative POST herbicides to control glyphosate-resistant Palmer amaranth. Although combination desmedipham + phenmedipham is no longer labeled, sugarbeet growers have access to leftover supplies and are trying to use this product as a rescue treatment when glyphosate fails to control Palmer amaranth. In rescue situations, Palmer amaranth is often 20–30 cm tall, because several days will pass before a failed POST application of glyphosate is noticed. Then a decision can be made to apply desmedipham + phenmedipham as a rescue treatment. Desmedipham + phenmedipham and desmedipham are labeled to control Palmer amaranth when applied at the cotyledon stage, but not when Palmer amaranth is larger. Dexter (1994) reported the efficacy of desmedipham + phenmedipham on *Amaranthus* spp. depends on the size of the weeds at the time of application, making this treatment a poor choice in a rescue situation.

Phenmedipham is available in the United States as the product Spin-Aid® (Bayer CropScience), which is labeled in red beet (*Beta vulgaris* L.) and spinach (*Spinacia oleracea* L.). However, phenmedipham is not registered in sugarbeet and is not labeled to control *Amaranthus* spp. (Anonymous 2009).

The Betamix (desmedipham 274 g ai ha^{-1} + phenmedipham 274 g ai ha^{-1}) and Betanex (desmedipham 547 g ai ha^{-1}) products allow a maximum rate of 547 g ai ha^{-1} for application to sugarbeet at the cotyledon and two true-leaf stages, whereas the rate is increased to 820 g ai ha^{-1} when sugarbeet reaches four true leaves. In a 2017 field experiment, researchers evaluated Palmer amaranth control at various sizes with desmedipham + phenmedipham in a simulated rescue application. In this trial, desmedipham + phenmedipham applied POST at 547 g ai ha^{-1} resulted in poor control of Palmer amaranth between 0.5 and 1.5 cm in height and in a high level of sugarbeet injury (Beiermann et al. 2018). Therefore, an experiment was initiated in 2019 to evaluate the response of Palmer amaranth and sugarbeet to desmedipham and phenmedipham in a greenhouse environment. The objectives of this experiment were to (1) determine the selectivity of desmedipham and phenmedipham between Palmer amaranth and sugarbeet at two distinct developmental stages, and (2) to determine the weed control and crop safety contribution of desmedipham and phenmedipham individually, within a formulated premixture of desmedipham + phenmedipham. Results from this experiment may help growers understand the utility of desmedipham + phenmedipham applied as a rescue treatment, and the data may support label expansion of phenmedipham to include sugarbeet or reregistration of desmedipham and desmedipham + phenmedipham in sugarbeet.

Materials and Methods

Site Description

A greenhouse experiment was conducted in 2019 at the University of Nebraska Panhandle Research and Extension Center, located near Scottsbluff, NE (41.89°N, 103.68°W). The first and second runs of the experiment were planted on June 12 and August 8, respectively. Palmer amaranth and sugarbeet were grown separately in plastic square pots 9 cm wide and 8 cm deep (T.O. Plastics, Clearwater, MN), and were filled with Sungro® potting mix (Sungro Horticulture, Agawam, MA). The potting mix contained no supplemental nutrients and was composed of 80% peat moss and 20% perlite. Greenhouse temperatures were maintained between 31 C (day) and 24 C (night). Supplemental lighting (P.L. Lighting Systems Inc., Beamsville, Ontario, Canada) was used to maintain a consistent photoperiod of 16 hours light and 8 hours dark. Plants were hand watered once daily throughout the duration of the experiments.

Treatment and Experimental Design

The experiment was laid out in a randomized complete block design with six and four replications in the first and second run, respectively. In the high-plains sugarbeet production region of Colorado and Nebraska, Palmer amaranth first begins to emerge approximately 1 wk before sugarbeet is planted (late April). Early-season weed control, (from planting to the two true-leaf stage of sugarbeet) is the most challenging time for control of Palmer amaranth. Therefore, Palmer amaranth and sugarbeet were planted at the same time in each run of the experiment to simulate a difficult weed-control scenario and subsequently were thinned to 1 plant pot^{-1} within 2 d after emergence. Palmer amaranth seed was treated with 5 mL of 0.1 M KNO_3 solution to help ensure adequate germination (Buhler and Hoffman 1999). Herbicide treatments were applied with a Generation III Research sprayer (DeVries Manufacturing, Hollandale, MN) equipped with an 8002 EVS TeeJet© nozzle (TeeJet Technologies, Wheaton, IL) calibrated to deliver the equivalent of 140 L ha^{-1} spray solution.

Three Palmer amaranth accessions were evaluated in both runs of the experiment: a local field population from Scottsbluff, NE; a confirmed triazine-resistant population from south-central Nebraska (Jhala et al. 2014); and a field population from Hays, KS. The first run of the experiment included two sugarbeet varieties, Crystal® W611NT GEM 100 and Beta® BTS 60RR27 Pro 50 (both from Betaseed Inc., Shakopee, MN). In the second run of the experiment, Beta BTS 60RR27 Pro 50 was used again along with Hilleshog® H7-1 (Hilleshog Seeds, Longmont, CO) and a noncommercial Hilleshog conventional variety.

The Betamix formulated premix of desmedipham (77.9 g ai L^{-1}) + phenmedipham (77.9 g ai L^{-1}) was applied at 274, 547, 1,090, and 2,190 g ai ha^{-1}, corresponding to each individual component being applied at 137, 274, 547, 1,090 g ai ha^{-1}. Desmedipham and phenmedipham were applied individually as the formulated products Betanex, and Spin-Aid, respectively, at 137, 274, 547, 1,090 g ai ha^{-1}, representing their equivalent individual rate in the Betamix product.

The second run of the experiment contained the same treatments as the first, with the additional rates of 137 and 4,380 g ai ha^{-1} of Betamix and equivalent rates of desmedipham and phenmedipham of 68 and 2,190 g ai ha^{-1}. Herbicide treatments were mixed with 1.5 % vol/vol methylated seed oil. The maximum labeled field rate of Betamix (desmedipham 274 g ai ha^{-1} + phenmedipham 274 g ai ha^{-1}) and Betanex (desmedipham 547 g ai ha^{-1}) for application to the cotyledon and two true-leaf stages of sugarbeet is 547 g ai ha^{-1}. Treatments of 547 g ai ha^{-1} hereafter in this article are referred to as a field rate or 1× rate, depending on context.

Treatments were applied at two separate timings on the basis of the size of Palmer amaranth and growth stage of sugarbeet. At the first application, both Palmer amaranth and sugarbeet were at the cotyledon stage. Palmer amaranth was 2 cm tall and sugarbeet was 1.5 cm tall 4 d after emergence. At the second application, Palmer amaranth was 7 cm tall and sugarbeet was 5 cm at the two true-leaf stage 12 d after emergence. Palmer amaranth and sugarbeet were treated together on the same day with the same treatment mixtures. Plants were not watered until the day after herbicide application to ensure effective herbicide absorption.

Data Collection

Plant death was assessed as a binary response (alive or dead) 2 wk after treatment. Treated plants failing to regrow after treatment and lacking any green tissues were considered dead. After assessing plant death, aboveground biomass of Palmer amaranth and sugarbeet was harvested and oven dried for 72 h at 50 C before weighing.

Statistical Analysis

Data from each run of the experiment were analyzed separately. Analysis was done with R software (R Core Team, 2019) by nonlinear regression using the DRC package (Ritz et al. 2015). Sugarbeet varieties responded similarly to all herbicide treatments, as did Palmer amaranth accessions. Therefore, all sugarbeet varieties were combined, and all Palmer amaranth accessions were combined. Hereafter in this article, discussion of plant response to herbicide treatments refers to either sugarbeet or Palmer amaranth, but not individual varieties or accessions. Variety and accessions were combined using nonlinear mixed-effects regression with the *medrc* package (Gerhard and Ritz, 2016). An LL.2 model was used for survival response, with sugarbeet variety and Palmer amaranth accession added as random effects, as shown in Equation 1:

$$f(x) = \frac{1}{1 + \exp(b(\log(x) - \log(e)))} \quad [1]$$

Biomass data were also combined using the *medrc* package (Gerhard and Ritz, 2016), and an LL.3 model was fit with variety and accession as random effects, as shown in Equation 2:

$$f(x) = c + \frac{1 - c}{1 + \exp(b(\log(x) - e))} \quad [2]$$

The selectivity index (SI) was calculated as described by Kniss and Streibig (2018) by dividing the estimated ED_{10} of sugarbeet by the ED_{90} of Palmer amaranth (Equation 3):

$$SI = \frac{[ED_{10}]crop}{[ED_{90}]weed} \quad [3]$$

The SI was only calculated using the mortality data and not biomass data.

Table 1. Parameter estimates and SEs of the two-parameter log-logistic model of survival of sugarbeet and Palmer amaranth treated at the cotyledon growth stage in a greenhouse experiment in 2019.

Herbicide	Run[a]	Sugarbeet[a] b (SE)[b]	Sugarbeet[a] LD_{50} (SE)	Sugarbeet[a] LD_{10} (SE)	Palmer amaranth[a] b (SE)	Palmer amaranth[a] LD_{50} (SE)	Palmer amaranth[a] LD_{90} (SE)	SI[c]
			g ai ha^{-1}			g ai ha^{-1}		
Desmedipham	1	—	—	—	0.6 (0.4)	19 (35)	663 (557)	—
	2	2.3 (0.7)	612 (110)	232 (62)	3.8 (1.1)	81 (12)	144 (37)	1.6
Phenmedipham	1	—	—	—	1.5 (0.4)	572 (90)	2,370 (1,008)	—
	2	2.5 (0.6)	1,665 (176)	681 (161)	2.9 (0.8)	129 (13)	275 (65)	2.5
Desmedipham + phenmedipham	1	16.7 (14,883)	2,235 (40,139)	1,959 (191,356)	2.7 (1.2)	232 (97)	528 (133)	3.7
	2	17.3 (112)	1,069 (140)	941 (900)	4.7 (0.9)	193 (16)	308 (37)	3.1

[a]Plant species and two separate experiment runs, modeled separately.
[b]Abbreviations: —, no response of model; *b*, slope; SI, selectivity index.
[c]Sugarbeet LD_{10}/Palmer amaranth LD_{90}.

Table 2. Parameter estimates (*b*, *d*, and *e*) and SEs of the three-parameter log-logistic model for sugarbeet and Palmer amaranth biomass treated with desmedipham and phenmedipham at the cotyledon stage in a greenhouse experiment in 2019.

Herbicide	Run[a]	Sugarbeet[a] b (SE)[b]	Sugarbeet[a] d (SE)	Sugarbeet[a] GR_{50} (SE)	Palmer amaranth[a] b (SE)	Palmer amaranth[a] d (SE)	Palmer amaranth[a] GR_{50} (SE)
				g ai ha^{-1}			g ai ha^{-1}
Desmedipham	1	—	—	—	0.8 (0.5)	1.1 (0.04)	3.5 (4.8)
	2	1.3 (0.3)	0.4 (0.05)	117 (24)	4.6 (5.9)	0.7 (0.03)	52 (19)
Phenmedipham	1	0.9 (0.4)	0.5 (0.05)	612 (172)	0.9 (0.3)	1.1 (0.07)	78 (35)
	2	1.4 (0.3)	0.4 (0.05)	231 (40)	2.8 (0.8)	0.7 (0.04)	57.9 (7.6)
Desmedipham + phenmedipham	1	1.4 (0.3)	0.5 (0.03)	591 (98)	3.2 (4)	1.1 (0.04)	131 (123)
	2	1.6 (0.2)	0.4 (0.05)	239 (26)	4.9 (5)	0.7 (0.03)	111 (24)

[a]Plant species and two separate experiment runs, modeled separately.
[b]Abbreviations: —, no response of model; *b*, slope; *d*, upper limit; GR_{50}, 50% biomass reduction.

Results and Discussion

Herbicide Dose-Response at Cotyledon Application Stage

Palmer amaranth response with desmedipham + phenmedipham resulted in an LD_{90} that was lower than a full labeled rate (547 g ai ha^{-1}) in both runs of the experiment, indicating an effective level of control (Table 1). Phenmedipham and desmedipham treatments had LD_{90} values greater than the 1× field rate in the first run of the experiment, indicating they did not provide effective control (Table 1). However, the LD_{90} of both phenmedipham and desmedipham was reduced in the second run of the experiment, and they both provided effective Palmer amaranth control at the 1× equivalent field rate (Table 1).

Phenmedipham was inconsistent in Palmer amaranth control. Phenmedipham resulted in the highest LD_{50} and provided almost 50% Palmer amaranth control at the 1× rate in the first run of the experiment. In the second run, phenmedipham provided effective Palmer amaranth control and resulted in a lower LD_{50} and GR_{50}, compared with desmedipham + phenmedipham, and provided greater than 90% control at the 1× rate (Tables 1 and 2). Desmedipham resulted in the lowest LD_{50} and GR_{50} for Palmer amaranth in both runs of the experiment and provided the greatest control efficacy compared with other treatments.

At the cotyledon stage, death was not observed in sugarbeet at the highest rates of desmedipham or phenmedipham applied alone, corresponding to a 2× field rate, in the first run of the experiment. The additional increased 4× rate in the second run achieved sugarbeet death and allowed for an LD_{50} to be calculated for all herbicide treatments in sugarbeet. Sugarbeet response to desmedipham + phenmedipham resulted in an LD_{10} above a labeled rate, indicating crop safety (Table 1). Desmedipham caused the highest mortality rate in sugarbeet, as evidenced by the lowest LD_{50} and GR_{50}, in the second run of the experiment (Tables 1 and 2). The LD_{50} for desmedipham is 612 g ai ha^{-1} (Table 1), relatively close to the field rate of 547 g ai ha^{-1}, indicating nearly 50% mortality, which is an unacceptable level of crop injury. Phenmedipham exhibited the greatest crop safety; it had the highest GR_{50} of sugarbeet in the first run, and the highest LD_{50} and a similar GR_{50} to desmedipham + phenmedipham in the second run (Tables 1 and 2).

As a general trend, equivalent rates in the second run provided better Palmer amaranth control than in the first run for desmedipham and phenmedipham (Table 1). Although adding additional rates in the second run improved model fit, the increased sugarbeet and Palmer amaranth injury observed between experiments may be best explained by normal variation in herbicide response observed from repeating experiments.

Desmedipham + phenmedipham provided effective control of cotyledon-sized Palmer amaranth in both runs of the experiment at the 1× field rate (Figure 1). The individual desmedipham and phenmedipham treatments controlled cotyledon Palmer amaranth at the 1× rate in the second run of the experiment only (Figure 1). Desmedipham + phenmedipham provided greater consistency of Palmer amaranth control and resulted in a similar LD_{50} for Palmer amaranth in both runs (Table 1).

Desmedipham caused an unacceptable level of sugarbeet injury at the 1× field rate, resulting in nearly 50% mortality (Figure 1). The estimated LD_{10} for cotyledon sugarbeet treated with phenmedipham and desmedipham + phenmedipham is greater than the 1× field rate for both herbicides, indicating that a low mortality rate is expected from these treatments (Table 1). However, sugarbeet injury was greater in the second run, indicated by reduced LD_{50} and LD_{10} (Table 1). Desmedipham + phenmedipham showed the most potential for effective control of Palmer amaranth

Table 3. Parameter estimates and SEs of the two-parameter log-logistic model of survival of sugarbeet and Palmer amaranth treated at the two true-leaf stage and 7 cm height, respectively, in a greenhouse experiment in 2019.

Herbicide	Run[a]	Sugarbeet[a] b (SE)[b]	Sugarbeet[a] LD_{50} (SE)	Sugarbeet[a] LD_{10} (SE)	Palmer amaranth[a] b (SE)	Palmer amaranth[a] LD_{50} (SE)	Palmer amaranth[a] LD_{90} (SE)	SI[c]
			g ai ha^{-1}			g ai ha^{-1}		
Desmedipham	1	—	—	—	5 (1.6)	876 (163)	1,361 (320)	—
	2	—	—	—	2.4 (0.7)	331 (37)	813 (204)	—
Phenmedipham	1	—	—	—	—	—	—	—
	2	—	—	—	2.4 (0.9)	1,766 (251)	4,392 (1,637)	—
Desmedipham + phenmedipham	1	3.2 (1.1)	2,285 (821)	1,158 (427)	2.7 (0.6)	1,545 (141)	3,439 (726)	0.3
	2	3.5 (1.2)	4,379 (316)	2,334 (494)	3.6 (1)	590 (49)	1,082 (190)	2.2

[a]Plant species and two separate experiment runs, modeled separately.
[b]Abbreviations: —, no response of model; b, slope; SI, selectivity index.
[c]Sugarbeet LD_{10}/Palmer amaranth LD_{90}.

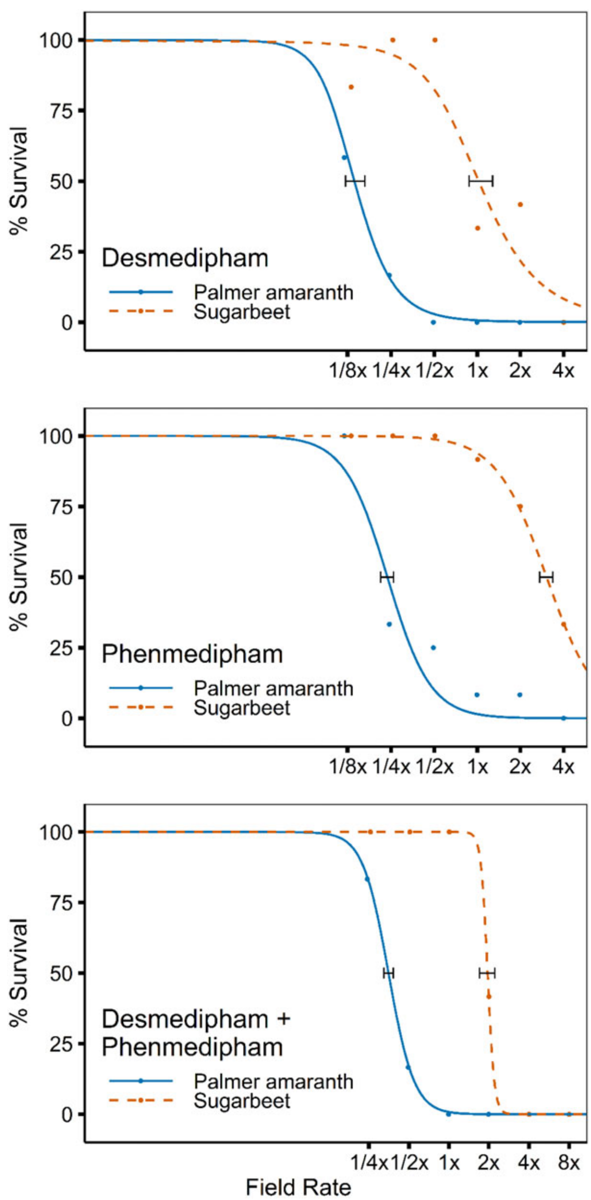

Figure 1. Survival of sugarbeet and Palmer amaranth treated at the cotyledon stage 2 wk after desmedipham and phenmedipham were applied alone or together. A two-parameter log-logistic model was used to determine the response. Horizontal error bars represent the SE of the *e* parameter (LD_{50}).

at the cotyledon stage; the combination provided consistent weed control and improved crop safety, compared to desmedipham and phenmedipham applied alone.

Herbicide Dose-Response at Two True-Leaf Application Stage

At the two true-leaf application timings, desmedipham and phenmedipham did not cause significant death in sugarbeet at the highest application rate in either run of the experiment (Table 3). Desmedipham + phenmedipham caused sugarbeet death, but only when applied at rates far exceeding labeled guidelines (Table 3). The estimated LD_{50} and GR_{50} were considerably lower in the first run compared to the second, which can be partially attributed to the additional higher rate in the second run improving model fit. The LD_{50} of both sugarbeet and Palmer amaranth at the two true-leaf application was increased for all herbicides compared with the cotyledon application timing. This observation agrees with the conclusions of Dexter (1994) and Weinlaeder and Dexter (1972) that both sugarbeet and redroot pigweed gain tolerance to desmedipham and phenmedipham as plants increase in size.

Desmedipham resulted in the lowest LD_{50} and GR_{50} of Palmer amaranth (Tables 3 and 4). The higher efficacy of desmedipham to control 7-cm tall Palmer amaranth follows the pattern of greater efficacy observed with desmedipham when applied at the cotyledon stage. Desmedipham + phenmedipham resulted in a higher LD_{50} for Palmer amaranth than desmedipham (Table 3). The 1× field rate of desmedipham + phenmedipham did not provide effective Palmer amaranth control in either run of the experiment; the highest level of control observed was near 50% (Figure 2). Phenmedipham did not cause Palmer amaranth death in the first run, and in the second run resulted in the highest estimated LD_{50} (Table 3). Phenmedipham applied at four times the equivalent of a field rate only provided 50% Palmer amaranth control (Figure 2).

None of the herbicides provided effective control of 7-cm tall Palmer amaranth at equivalent labeled field rates. Desmedipham resulted in lower LD_{50} and lower GR_{50} values compared to phenmedipham, indicating that desmedipham provides greater efficacy in controlling Palmer amaranth, but desmedipham also caused greater sugarbeet injury compared with phenmedipham (Tables 3 and 4). Desmedipham contributed to more of the observed weed control activity compared to phenmedipham in the formulated Betamix product. The increased weed control efficacy of desmedipham compared to phenmedipham has been observed at the field level. Adbollahi and Ghadiri (2004) found

Table 4. Parameter estimates (*b*, *d*, and *e*) and SEs of the three-parameter log-logistic model for sugarbeet and Palmer amaranth biomass treated with desmedipham and phenmedipham at the two true-leaf sugarbeet growth stage in a dose-response experiment in 2019.

		Sugarbeet[a]			Palmer amaranth[a]		
Herbicide	Run[a]	*b* (SE)[b]	*d* (SE)	GR_{50} (SE)	*b* (SE)	*d* (SE)	GR_{50} (SE)
				g ai ha^{-1}			g ai ha^{-1}
Desmedipham	1	0.5 (0.2)	1.3 (0.3)	257 (144)	1.1 (0.2)	2.3 (0.1)	216 (35)
	2	1.3 (0.3)	0.6 (0.08)	930 (233)	1.7 (0.3)	1.6 (0.1)	62 (11)
Phenmedipham	1	0.8 (0.2)	1.3 (0.3)	914 (463)	1.4 (0.4)	2.4 (0.1)	980 (184)
	2	1.8 (0.7)	0.6 (0.1)	1,415 (357)	0.6 (0.1)	1.6 (0.1)	163 (52)
Desmedipham + phenmedipham	1	0.6 (0.2)	1.3 (0.3)	647 (310)	1.1 (0.2)	2.3 (0.1)	416 (71)
	2	1.2 (0.3)	0.6 (0.1)	1,430 (347)	1.4 (0.2)	1.6 (0.1)	145 (19)

[a]Plant species and two separate experiment runs, modeled separately.
[b]Abbreviations: *b*, slope; *d*, upper limit; GR_{50}, 50% biomass reduction.

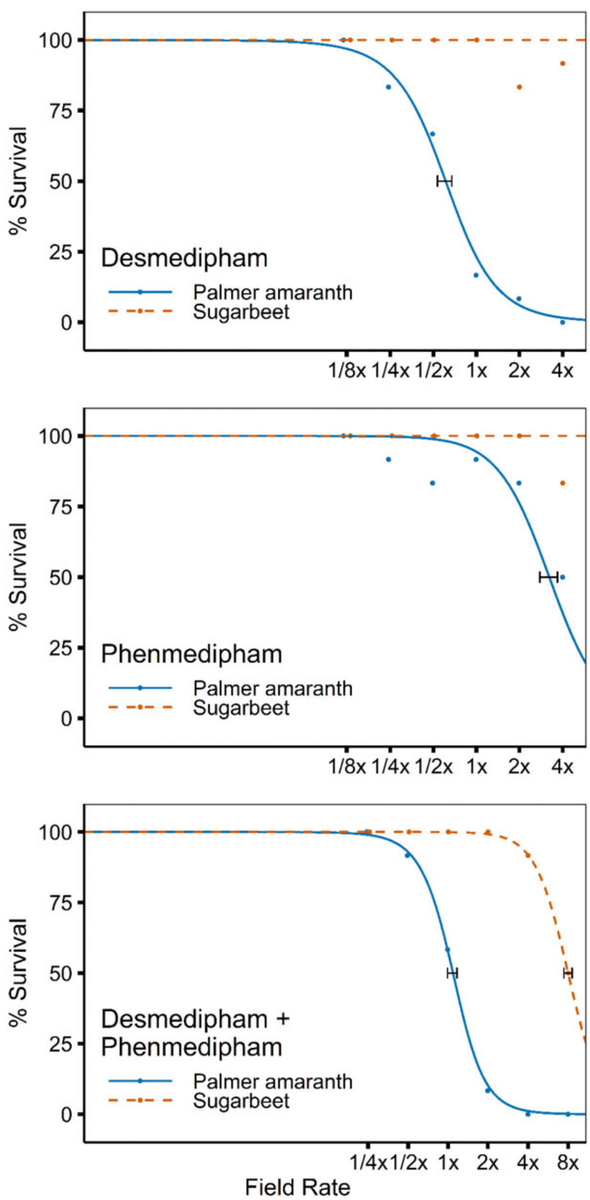

Figure 2. Survival of sugarbeet at the two true-leaf stage and Palmer amaranth when 7 cm tall at 2 wk after desmedipham or phenmedipham were applied alone or together. A two-parameter log-logistic model was used to determine the response. Horizontal error bars represent the SE of the *e* parameter (LD_{50}).

the control of common lambsquarters and redroot pigweed improved when desmedipham + phenmedipham was applied, compared with phenmedipham applied alone. Hendrick et al. (1974) reported that redroot pigweed could metabolize phenmedipham at an accelerated rate compared to desmedipham, and a similar mechanism may be responsible for the increased efficacy of desmedipham compared to phenmedipham for control of Palmer amaranth.

Selectivity

A selectivity index greater than 2 indicates there is potential selectivity for a product to be used safely in a crop (Bartley 1993). At the cotyledon application stage, all three herbicide treatments achieved selectivity between Palmer amaranth and sugarbeet, meaning that the rate estimated to cause 90% mortality in Palmer amaranth was lower than the rate estimated to cause 10% mortality in sugarbeet. Achieving selectivity in a controlled dose-response experiment indicates there is potential for a field application of the herbicide at specific rates that will cause acceptable control of a weed species without excessive crop injury.

At the cotyledon application timing, desmedipham + phenmedipham had the highest calculated selectivity index (3.7 to 3.1), whereas desmedipham had the lowest (1.6) (Table 1). Palmer amaranth treated with desmedipham resulted in the lowest LD_{90}, indicating desmedipham can provide 90% Palmer amaranth control at a lower rate than phenmedipham or desmedipham + phenmedipham (Table 1). However, sugarbeet treated with desmedipham resulted in a lower LD_{10} compared with other treatments, reducing the selectivity (Table 1). Phenmedipham provided less control of Palmer amaranth at equivalent rates to desmedipham but resulted in a greater selectivity index (2.5), due to reduced injury in sugarbeet, indicated by a higher LD_{10} (Table 1).

At the two true-leaf application timing, selectivity could only be calculated for desmedipham + phenmedipham, because an LD_{10} of sugarbeet could not be estimated for other treatments (Table 3). Selectivity of desmedipham + phenmedipham was not achieved in the first run of the experiment between Palmer amaranth and sugarbeet, and the resulting selectivity index was less than 1, which indicates the application rate required to achieve control of Palmer amaranth is greater than the rate causing 10% mortality in sugarbeet (Table 3). In the second run of the experiment, the selectivity index for desmedipham + phenmedipham is 2.2 (Table 3). Although a value greater than 2 demonstrates potential for use in the crop, an LD_{10} in sugarbeet and an LD_{90} in Palmer

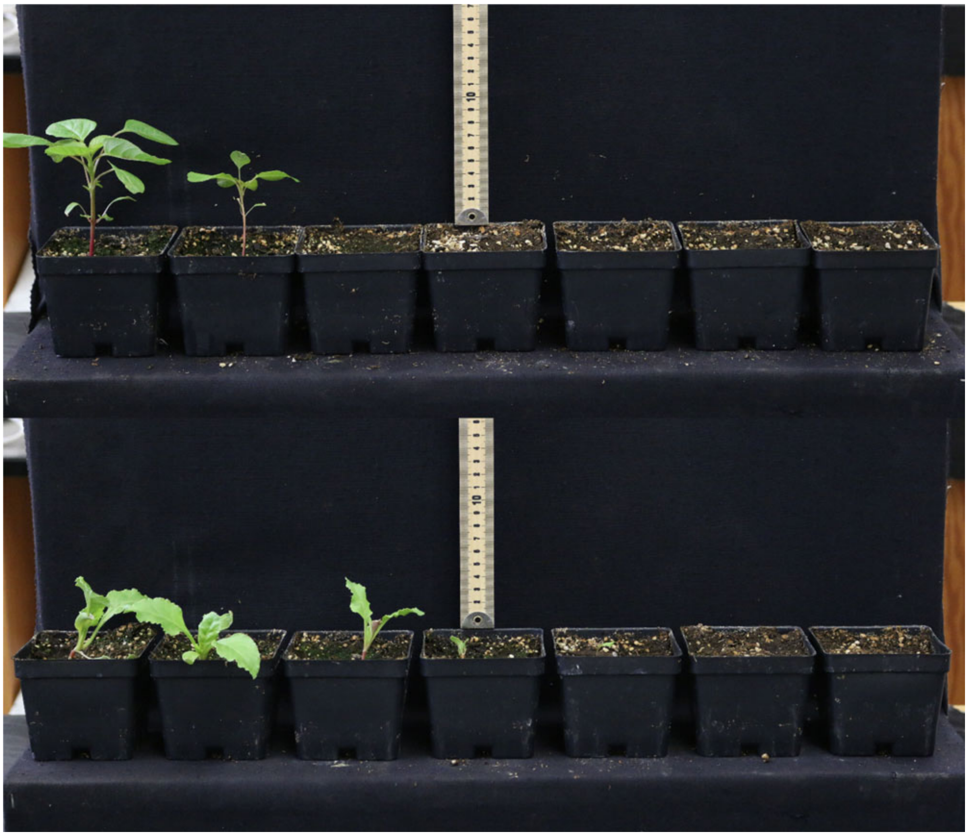

Figure 3. Palmer amaranth and sugarbeet, treated with desmedipham + phenmedipham at the cotyledon stage, 10 d after application. Plants are arranged starting with nontreated control at the left, moving to the right up to the 8× rate.

amaranth were achieved at a use rate of 1,082 g ai ha^{-1}, which is twice the maximum labeled rate.

The selectivity of desmedipham + phenmedipham at the two true-leaf application was reduced compared with the cotyledon application (Tables 1 and 3). The tolerance of sugarbeet to desmedipham + phenmedipham was increased at the two true-leaf stage compared to the cotyledon stage, as evidenced by the increased LD_{50} and GR_{50}. However, the tolerance of Palmer amaranth to desmedipham + phenmedipham also increased from the cotyledon stage and required a higher rate to reach 90% mortality. This increase in the rate required to control Palmer amaranth reduced the range between rates that would selectively control Palmer amaranth and not cause excessive injury in sugarbeet.

Practical Implications

The 1× rate of desmedipham + phenmedipham controlled Palmer amaranth and resulted in a low mortality rate in sugarbeet when applied at the cotyledon stage (Figure 1). However, death is not a complete indication of crop injury; growers applied desmedipham + phenmedipham knowing that substantial injury would occur. Figure 3 shows desmedipham + phenmedipham applied to cotyledon sugarbeet 10 d after treatment. Sugarbeet treated with the 1× labeled field rate had a high amount of foliar injury and severe stunting compared to the nontreated control. Sugarbeet treated with the 1× field rate were considered as surviving if they began regrowth; however, yield loss is expected from this level of crop injury. The estimated GR_{50} for cotyledon sugarbeet treated with desmedipham + phenmedipham was near the 1× field rate in the first run and lower that the 1× field rate in the second run, revealing the high amount of growth reduction and crop injury caused (Table 3).

The potential for effective Palmer amaranth control at the two true-leaf application was not evident, because none of the herbicide treatments provided effective Palmer amaranth control without risking unacceptable rates of plant mortality. The 1× rate of desmedipham + phenmedipham resulted in 50% Palmer amaranth mortality, whereas the 1× desmedipham rate resulted in 75% Palmer amaranth mortality (Figure 2), neither of which is an acceptable level of control. The phenmedipham treatment provided the poorest control of Palmer amaranth, as indicated by the higher LD_{50} and GR_{50} values (Tables 3 and 4).

The level of sugarbeet injury sustained from the 1× desmedipham + phenmedipham treatment at the two true-leaf application shows improved crop tolerance, in comparison to the cotyledon stage (Figures 3 and 4). However, a labeled application at two true leaves does cause crop injury without providing an effective level of Palmer amaranth control. The maximum application rate of desmedipham and desmedipham + phenmedipham increased to 820 g ai ha^{-1} when sugarbeet reached four true leaves; however, the possibility of control at this rate is not evident on the basis of the performance of equivalent applications to 7-cm tall Palmer amaranth. Furthermore, Palmer amaranth that emerged at the same time as sugarbeet would be taller than 7 cm when the four true-leaf stage is reached, further diminishing control.

The lack of control achieved on 7-cm tall Palmer amaranth reveals that the success of a rescue treatment with desmedipham, phenmedipham, or desmedipham + phenmedipham is not possible even when applying rates exceeding label recommendations. In a rescue situation, Palmer amaranth will be 10–20 cm tall

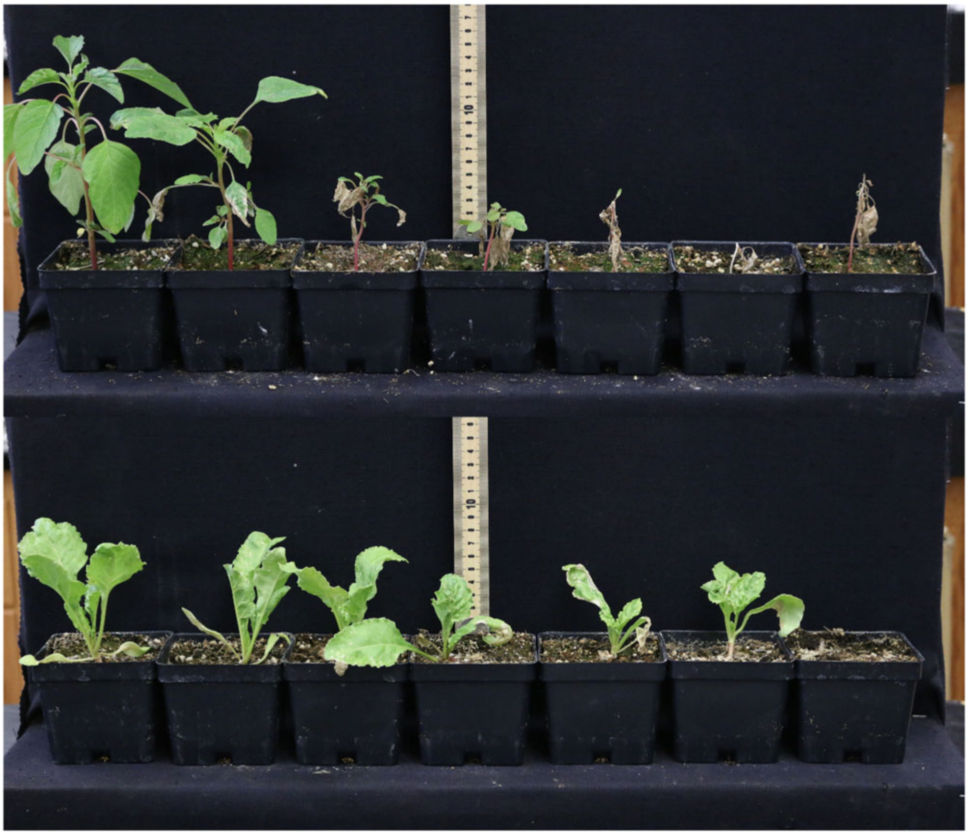

Figure 4. Palmer amaranth and sugarbeet, treated with desmedipham + phenmedipham when they were 7cm tall and at the two true-leaf stage, respectively, at 10 d after application. Plants are arranged starting with nontreated control at the left, moving to the right up to the 8× rate.

when glyphosate failure is identified and a rescue treatment can be made. Anecdotally, growers in the Panhandle of Nebraska have attempted late-season rescue treatments with desmedipham + phenmedipham at rates exceeding 1,457 g ai ha^{-1} and failed to control glyphosate-resistant Palmer amaranth. There is potential for desmedipham + phenmedipham to control cotyledon-sized Palmer amaranth. However, application timing would be highly critical to the success of control, and growers would have to accept the potential of a high level of crop injury. Desmedipham + phenmedipham may still be effective when used in a split application or microrate program in which single application rates were reduced to improve crop injury (Dale et al. 2006; Dexter 1994); however, returning to such intensive weed management is likely unpalatable after years of relying on glyphosate for broadleaf weed control in sugarbeet.

Sugarbeet growers using desmedipham or phenmedipham in any type of POST program will have to accept the increased crop injury and herbicide cost compared to glyphosate (Kniss et al. 2004; Wilson 1999). Desmedipham and phenmedipham have limited utility for controlling Palmer amaranth in western Nebraska and will not provide control of Palmer amaranth as a rescue treatment. With desmedipham and phenmedipham no longer labeled for US sugarbeet, there is a critical need for alternative herbicides to control glyphosate-resistant weeds, especially early in the season.

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References

Abdollahi F, Ghadiri H (2004) Effect of separate and combined applications of herbicides on weed control and yield of sugar beet. Weed Technol 18: 968–976

Anonymous (2011) Betamix® herbicide product label. Research Triangle Park, NC: Bayer CropScience

Anonymous (2010) Betanex® herbicide product label. Research Triangle Park, NC: Bayer CropScience

Anonymous (2009) Spin-Aid® herbicide product label. Research Triangle Park, NC: Bayer CropScience

Bartley MR (1993) Assessment of herbicide selectivity. Pages 57–73 *in* Streibig JC, Kudsk P, eds. Herbicide Bioassays. Boca Raton, FL: CRC Press

Beiermann CW, Lawrence NC, Knezevic SZ, Jhala A, Creech CF (2018) Rescue treatment options for glyphosate-resistant palmer amaranth in sugarbeet. Pages 25–26 *in* Proceedings of the Western Society of Weed Science. Garden Grove, CA: Weed Science Society of America

Brimhall PB, Chamberlain EW, Alley HP (1965) Competition of annual weeds and sugar beets. Weeds 13:33–35

Buhler DD, Hoffman ML, eds (1999) Andersen's Guide to Practical Methods of Propagating Weeds and Other Plants. Lawrence, KS: Allen Press. 5 p

Chahal PS, Aulakh JS, Jugulam M, Jhala AJ (2015) Herbicide-resistant Palmer amaranth (*Amaranthus palmeri* S. Wats.) in the United States. Mechanisms of resistance, impact, and management. Pages 1–40 *in:* Price AJ, Kelton JA, Sarunaite L (eds). Herbicides, Agronomic Crops, and Weed Biology. New York, NY: In Tech Scientific Publisher

Chahal PS, Varanasi VK, Jugulam M, Jhala AJ (2017) Glyphosate-resistant palmer amaranth (*Amaranthus palmeri*) in Nebraska: confirmation, EPSPS gene amplification, and response to post corn and soybean herbicides. Weed Technol 31:80–93

Culpepper AS, Grey TL, Vencill WK, Kichler JM, Webster TM, Brown SM, York AC, Davis JW, Hanna WW (2006) Glyphosate-resistant palmer amaranth (*Amaranthus palmeri*) confirmed in Georgia. Weed Sci 54: 620–626

Dale TM, Renner KA, Kravchenko AN (2006) Effect of herbicides on weed control and sugarbeet (*Beta vulgaris*) yield and quality. Weed Technol 20: 150–156

Dawson JH (1965) Competition between irrigated sugar beets and annual weeds. Weeds 13:245–249

Dexter AG (1994) History of sugarbeet (*Beta vulgaris*) herbicide rate reduction in North Dakota and Minnesota. Weed Technol 8:334–337

Dexter AG, Luecke JL (1998) Special survey of micro-rate, 1998. Sugarbeet Research & Education Board. http://archive.sbreb.org/Research/weed/weed98/98P64.HTM Accessed: April 1, 2020

[EPA] Environmental Protection Agency (2014) Product cancellation order for certain pesticide registrations. US Federal Register 79:14247–14250

Eshel Y, Schweizer EE, Zimdahl RL (1976) Sugarbeet tolerance of post-emergence applications of desmedipham and ethofumesate. Weed Res 16: 249–254

Fernandez-Cornejo J, Wechsler S, Milkove D (2016) The adoption of genetically engineered alfalfa, canola, and sugarbeets in the United States. Washington DC: US Department of Agriculture Economic Research Service. 163 p

Gerhard D, Ritz C (2016) An introduction to the package medrc. https://doseresponse.github.io/medrc/articles/medrc.html. Accessed: March 27, 2020

Heidari G, Nasab ADM, Javanshir A, Khoie FR, Moghaddam M (2007) Influence of redroot pigweed (*Amaranthus retroflexus* L.) emergence time and density on yield and quality of two sugar beet cultivars. J Food Agric Environ 5:261–266

Hendrick LW, Meggitt WF, Penner D (1974) Basis for selectivity of phenmedipham and desmedipham on wild mustard, redroot pigweed, and sugar beet. Weed Sci 22:179–184

Jha P, Norsworthy JK (2009) Soybean canopy and tillage effects on emergence of palmer amaranth (*Amaranthus palmeri*) from a natural seed bank. Weed Sci 57:644–651

Jha P, Norsworthy JK, Riley MB, Bielenberg DG, Bridges Jr. W (2008) Acclimation of palmer amaranth (*Amaranthus palmeri*) to shading. Weed Sci 56:729–734

Jhala AJ, Sandell LD, Rana N, Kruger GR, Knezevic SZ (2014) Confirmation and control of triazine and 4-hydroxyphenylpyruvate dioxygenase-inhibiting herbicide-resistant palmer amaranth (*Amaranthus palmeri*) in Nebraska. Weed Technol 28:28–38

Khan MFR (2010) Introduction of glyphosate-tolerant sugar beet in the United States. Outlooks Pest Manage 21:38–41

Knezevic SZ, Klein RN, Shea PJ, Creech CF, Kruger GR, Ogg CL, Jhala AJ, Proctor CA, Lawrence NC (2020) Guide for weed, disease, and insect management in Nebraska. UNL Extension publication EC130. Lincoln, NE: University of Nebraska–Lincoln

Kniss AR, Lawrence NC (2020) Efficacy of metamitron applied PRE in the high plains sugar beet production region. Page 224 *in* Proceedings of the Western Society of Weed Science. Maui, HI: Weed Science Society of America

Kniss AR, Streibig JC (2018) Statistical analysis of agricultural experiments using R. https://rstats4ag.org. Accessed: March 26, 2020

Kniss AR, Wilson RG, Martin AR, Burgener PA, Feuz DM (2004) Economic evaluation of glyphosate-resistant and conventional sugar beet. Weed Technol 18:388–396

Morishita DW (2017) Impact of glyphosate-resistant sugar beet. Pest Manage Sci 74:1050–1053

R Core Team (2019). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Accessed: September 18, 2019. https://www.R-project.org/

Ritz C, Baty F, Streibig JC, Gerhard D (2015) Dose-response analysis using R. PLoS One 10:e0146021

Sauer J (1957) Recent migration and evolution of the dioecious amaranths. Evolution 11:11–31

Schultz W, Lawrence NC (2019) Palmer amaranth interference in sugarbeet. Page 16 *in* Proceedings of the Western Society of Weed Science. Denver, CO: Weed Science Society of America

Schweizer EE, Lauridson TC (1985) Powell amaranth (*Amaranthus powellii*) interference in sugarbeet (*Beta vulgaris*). Weed Sci 33:518–520

Soltani N, Dille JA, Burke IC, Everman WJ, VanGessel MJ, Davis VM, Sikkema PH (2016) Potential corn yield losses from weeds in North America. Weed Technol 30:979–984

Soltani N, Dille JA, Burke IC, Everman WJ, VanGessel MJ, Davis VM, Sikkema PH (2017) Perspectives on potential soybean yield losses from weeds in North America. Weed Technol 31:148–154

Soltani N, Dille JA, Robinson DE, Sprague CL, Morishita DW, Lawrence NC, Kniss AR, Jha P, Felix J, Nurse RE, Sikkema PH (2018) Potential yield loss in sugarbeet due to weed interference in the United States and Canada. Weed Technol 32:749–753

Starke RJ, Renner KA, Penner D, Roggenbuck FC (1996) Influence of adjuvants and desmedipham plus phenmedipham on velvetleaf (*Abutilon theophrasti*) and sugarbeet response to triflusulfuron. Weed Sci 44:489–495

Stebbing JA, Wilson RG, Martin AR, Smith JA (2000) Row spacing, redroot pigweed (*Amaranthus retroflexus*) density, and sugarbeet (*Beta vulgaris*) cultivar effects on sugarbeet development. J Sugar Beet Res 37:11–31

Steckel LE, Sprague CL, Stoller EW, Wax LM (2004) Temperature effects on germination of nine *Amaranthus* species. Weed Sci 52:217–221

Vieira BC, Samuelson SL, Alves GS, Gaines TA, Werle R, Kruger GR (2017) Distribution of glyphosate-resistant *Amaranthus* spp. in Nebraska. Pest Manag Sci 74:2316–2324

Ward SM, Webster TM, Steckel LE (2013) Palmer amaranth (*Amaranthus palmeri*): a review. Weed Technol 27:12–27

Weinlaeder RA, Dexter AG (1972) Several factors influencing sugarbeet injury in the field and growth chamber. Page 33 *in* Proceedings of the North Central Weed Control Conference. Winnipeg, MB, Canada: Weed Science Society of America

Wilson RG (1999) Response of nine sugarbeet (*Beta vulgaris*) cultivars to postemergence herbicide applications. Weed Technol 13:25–29

Wilson RG, Yonts CD, Smith JA (2002) Influence of glyphosate and glufosinate on weed control and sugarbeet (*Beta vlugaris*) yield in herbicide-tolerant sugarbeet. Weed Technol 16:66–73

Zimdahl RL, Fertig SN (1967) Influence of weed competition on sugar beets. Weeds 15:336–339