Performance and Safety of Acifluorfen in Processing Red Beets

Lynn M. Sosnoskie[1] and Thierry Besançon[2]

Keywords. ***Amaranthus powellii*** **S. Wats.,** ***Ambrosia artemesiifolia*** **L.,** ***Beta vulgaris*** **L. subsp.** ***vulgaris*****, common ragweed, herbicide injury, Powell amaranth**

Abstract. Field trials were conducted in New York during 2021 and 2022 to evaluate acifluorfen herbicide as an alternative to postemergence (POST) pigweed management for red beets (*Beta vulgaris* L. spp. *vulgaris*). Acifluorfen was applied at 0.07, 0.14, and 0.28 kg·ha^{-1} a.i. to red beets at either the 6- to 8-leaf or 10- to 12-leaf developmental stages. Acifluorfen provided 68% to 96% control of Powell amaranth (*Amaranthus powellii* S. Watson), with significantly greater efficacy at higher application rates and earlier timing when weeds were smaller. Conversely, common ragweed control was considerably lower (16%–50%), likely because of the presence of larger plants at the time of application. Red beet herbicide injury, characterized by leaf necrosis, bronzing, and stunting, was significantly influenced by both the application rate and timing. Higher rates caused greater injury; applications at the 6- to 8-leaf stage resulted in substantially more damage than applications at the 10- to 12-leaf stage. Environmental conditions likely influenced injury severity, with higher rainfall and more hours of relative humidity ≥90% in 2021 causing greater leaf loss and crop stunting than in 2022. Applications of acifluorfen at the 6- to 8-leaf stage significantly reduced both red beet leaf biomass and root yield compared with the later application. These results demonstrate that acifluorfen can effectively control Powell amaranth in red beets, although application timing is crucial to minimize crop injury and yield reduction. A later application (10- to 12-leaf stage) is recommended, especially when environmental stress may exacerbate herbicide injury. Additional research is needed to fully evaluate the utility of acifluorfen in red beet production systems across diverse environments and weed pressure scenarios.

The United States produces approximatey 17,000 acres of red beets across 7500 farms (US Department of Agriculture-National Agricultural Statistic Service 2025). New York and Wisconsin are the leading states in production acreage, with approximately 3770 acres each (US Department of Agriculture-National Agricultural Statistic Service 2025). Seventy percent of New York red beets are grown for processing, with the remaining 30% allocated for fresh market sales (Pethybridge et al. 2018; US Department of Agriculture-National Agricultural Statistic Service 2025). Like New York, Wisconsin red beet acres primarily support a processing industry (US Department of Agriculture-National Agricultural Statistic Service 2025). To maximize marketable yields, red beets are intensively managed with respect to crop production (D'Egidio et al. 2019; Kikkert et al. 2010) and pest control practices (Chancia et al. 2021; Pethybridge et al. 2018), which include weed suppression (Colquhoun et al. 2016; Robinson et al. 2013).

Red beets exhibit slow emergence and growth and are also short in stature; these characteristics make them poor competitors with weeds, particularly the rapidly germinating summer annual species, such as pigweeds (*Amaranthus* spp.) (Carvalho et al. 2010; Colquhoun et al. 2016; Hewson and Roberts 1973; Robinson et al. 2013). Even though the reported critical period of weed removal (corresponding to the period of the crop growth cycle during which weeds must be controlled to prevent yield losses) in red beets ranges from 4 to 6 weeks after germination (Kavaliauskaitė and Bobinas 2006; Kołota and Osińska 1998), season-long weed control is necessary. Red beets in New York and other regions with rocky or heavy soils are harvested using top-pulling machinery (Pethybridge et al. 2018; Stivers 1999). Standing weeds can physically interfere with lifting and cutting operations, resulting in yield loss (Sosnoskie LM, personal observation).

Because of limited economically viable alternatives, red beet growers primarily rely on synthetic herbicides for weed control despite having fewer registered options than other crops (Colquhoun et al. 2016; Robinson et al. 2013). Additionally, the labeled chemistries have narrow spectrums of control, necessitating multiple postemergence (POST) treatments, often at low doses for crop safety (Colquhoun et al. 2016; Robinson et al. 2013). The current lack of herbicide options can be partially attributed to the release of glyphosate-resistant (GR) sugar beet (Beiermann et al. 2021; Colquhoun et al. 2016). Glyphosate has enabled sugar beet [*Beta vulgaris* subsp. *vulgaris* (var. *saccharifera*) L.] growers to achieve higher levels of weed control with fewer applications, reduced the need for strict timing schedules, improved crop safety, and reduced costs (Beiermann et al. 2021; Kemp et al. 2009; Khan 2010; Kniss et al. 2004; Morishita 2018; Wilson and Sbatella 2011). The widespread adoption of GR technology for sugar beets has limited new herbicide registrations and likely contributed to the loss of other active ingredients, such as pyrazon (Beiermann et al. 2021; Colquhoun et al. 2016).

The evolution of GR weeds, including two aggressive pigweed species, waterhemp [*Amaranthus tuberculatus* (Moq.) Sauer] and Palmer amaranth (*Amaranthus palmeri* S. Watson), has reinvigorated efforts to identify effective herbicide chemistries for sugar beets (Beiermann et al. 2021). This includes

Received for publication 8 Apr 2025. Accepted for publication 29 May 2025.

Published online 31 Jul 2025.

[1]School of Integrative Plant Sciences - Horticulture Section, Cornell AgriTech, New York State Agricultural Experiment Station, 221 Hedrick Hall, Geneva NY 14456, USA

[2]Department of Plant Biology, School of Environmental and Biological Sciences Rutgers, The State University of New Jersey, 59 Dudley Road, New Brunswick, NJ 08901-8525, USA

The authors acknowledge funding support for this research by the New York Vegetable Research Council and Association and the New York State Department of Agriculture and Markets. We thank Cornell AgriTech's Field Research Unit as well as members of the Specialty Crop Weed Science laboratory, especially Elizabeth Maloney, for assistance with fieldwork. We also extend our gratitude to Paul Tomion for providing field space in 2022.

No conflicts of interests have been declared.

Mention of trademark, proprietary product, or vendor does not constitute a guarantee or warranty of the product by the authors and does not imply its approval to the exclusion of other products or vendors that also may be suitable.

L.M.S. is the corresponding author. E-mail: lms438@cornell.edu.

https://doi.org/10.21273/HORTTECH05667-25

acifluorfen, a protoporphyrinogen oxidase (PPO) inhibitor (Weed Science Society of America Group 14) which is labeled for use on soybean and edamame [*Glycine max* (L.) Merr.], peanut (*Arachis hypogaea* L.), rice (*Oryza sativa* L.), and strawberry (*Fragaria* × *ananassa* Duchesne) (United Phosphorus Limited 2023), thus providing effective POST control of a wide range of broadleaf weed species, including pigweeds, common ragweed (*Ambrosia artemisiifolia* L.), morningglories (*Ipomoea* spp.), cocklebur (*Xanthium strumarium* L.), and jimsonweed (*Datura stramonium* L.) (Aicklen et al. 2022; Barrentine 1978; Gossett and Toler 1999; Lee and Oliver 1982; Mayo et al. 1995; Oliver and Howe 1980; Sperry et al. 2017). Peters et al. (2021, 2022, 2023) reported that acifluorfen applied at 0.28 kg·ha^{-1} a.i. effectively controls waterhemp plants shorter than 5 to 10 cm in sugar beets. While acifluorfen carries a risk of crop injury, sugar beet growers have reported that yield loss from waterhemp competition exceeds the impact of possible herbicide damage (Peters et al. 2021, 2022, 2023). Since 2021, Section 18 Emergency Use Labels have been approved for the use of acifluorfen (Ultra Blazer®; United Phosphorus Limited NA Inc., King of Prussia, PA, USA) to control GR and invasive pigweeds in sugar beets in several states at a rate of 0.28 kg·ha^{-1} a.i. (US Environmental Protection Agency 2025).

Red beet production faces significant weed management challenges. Many common species, like pigweeds, are not effectively managed by currently registered herbicides (Sosnoskie LM, personal observation). Regarding residual products, cycloate and *S*-metolachlor (Weed Science Society of America Group 15) provide "good" pigweed control. However, their effectiveness lasts approximately 30 d, which is insufficient for the 100-d (or longer) growing season for red beet. The limited POST options, triflusulfuron-methyl, phenmedipham, and clopyralid, have historically provided "fair" to "poor" pigweed control in New York. Therefore, this research evaluated the performance and safety of acifluorfen for red beets to identify a potential alternative for improved pigweed management.

Materials and methods

Study sites. Field studies that assessed acifluorfen use for red beets were conducted at Cornell AgriTech in Geneva, NY, USA (42°86′N, 77°02′W), in 2021 and 2022, and at a commercial red beet production field 12 km from Cornell AgriTech, near Hall, NY, USA (42°79′N, 77°03′W) in 2022. Soil at both sites was a Honeoye loam (fine-loamy, mixed, semiactive, mesic Glossic Hapludalfs) with 38% sand, 44% silt, 18% clay, 2.5% organic matter, and a pH of 6.3. Temperature, rainfall, and relative humidity (RH) data during the 2021 and 2022 production seasons were collected from a permanent weather station located at Cornell AgriTech (Table 1).

Plant material and planting conditions. All fields were moldboard-plowed and disked before planting to eliminate emerged weeds. In 2021, 'Ruby Queen' beets (Seneca Foods, Dayton, WA, USA) were planted on 10 Jun at a density of 60 seeds/m^2 and a depth of 1.5 cm in rows spaced 76 cm apart. 'Ruby Queen' was selected for use in this study because it is a frequently planted, affordable, disease-resistant cultivar with preferred root characteristics for the processing industry. Fertilizer (10 N:5 P:10 K; Phelps Supply Inc., Phelps, NY, USA) was broadcast at 336 kg·ha^{-1} and incorporated ahead of planting. The same type and amount of fertilizer was banded at seeding. In 2022, 'Ruby Queen' beets were planted on 10 May (Hall) and 16 May (Cornell AgriTech) at 150 seeds/m^2, which more closely reflects a commercial seeding density. Fertilizer was the same as in 2021. In 2021, *S*-metolachlor (Dual Magnum®; Syngenta Crop Protection, Inc., Greensboro, NC, USA) at 0.72 kg·ha^{-1} a.i. and ethofumesate (Nortron®; Bayer Crop Science, St. Louis, MO, USA) at 1.1 kg·ha^{-1} a.i. were applied postplanting but before weed emergence (PRE) to the entire trial site, including the control. Both herbicides are labeled for use in New York on red beets and were applied to reduce initial weed competition and improve crop stand establishment. The same PRE herbicides and rates were applied in 2022, except the Hall site was treated with ethofumesate at 2.1 kg·ha^{-1} a.i. Cornell AgriTech trials were irrigated within 24 h of planting (1.3 cm) to facilitate crop germination and incorporate herbicides. The Hall site was not irrigated, but it received 1.3 cm of precipitation within 10 d of planting. In addition to PRE treatments, all plots at both sites received POST applications at 26 d after seeding (DAS) using herbicides labeled for red beets. Hall received clopyralid (Spur®; Albaugh LLC, Ankeny, IA, USA) at 0.21 kg·ha^{-1} a.e. plus ethofumesate at 0.184 kg·ha^{-1} a.i. Cornell AgriTech received clopyralid (Stinger®; Corteva Agriscience LLC, Indianapolis, IN, USA) at 0.233 kg·ha^{-1} a.e. plus phenmedipham (Spin-Aid®; Belchim Crop Protection US Corp., Wilmington, DE, USA) at 0.182 kg·ha^{-1} a.i. The herbicides were selected to target emerged weed species at each site and for their lack of phytotoxicity to red beets when applied over the top.

Acifluorfen trials. This study had a two-factor factorial, with the acifluorfen rate and red beet developmental stage at the time of application as the main factors. These were arranged in a randomized complete block design with four replications per treatment for each site-year. A control that received PRE and early POST applications but no acifluorfen was included for comparison. Individual plots had a width of 1.52 m and length of 7.6 m. Acifluorfen (Ultra Blazer®; United Phosphorus Limited NA Inc., King of Prussia, PA, USA) was applied at 0.07, 0.14, and 0.28 kg·ha^{-1} a.i. to beets, either at the 6- to 8-leaf or the 10- to 12-leaf red beet developmental stages. In 2021, the 6- to 8-leaf and 10- to 12-leaf treatments occurred at 29 DAS and 41 DAS, respectively. In 2022, the 6- to 8-leaf and 10- to 12-leaf treatments occurred at 30 to 32 DAS and 50 to 52 DAS, respectively. Spray solutions included NIS (WETCIT; Oro Agri Inc., Fresno, CA, USA) at 0.125% v/v. Acifluorfen treatments were applied using a CO_2 backpack sprayer fitted with two TeeJet 8002VS nozzles (TeeJet Technologies Inc., Glendale Heights, IL, USA) spaced 46 cm apart and calibrated to deliver a volume of 187 L·ha^{-1} at 276 kPa. Environmental data for each application event are presented in Table 2. Treatments were designed according to the results reported by Peters et al. (2021, 2022, 2023) who recommended a single acifluorfen application at 0.280 kg·ha^{-1} a.i. and a spray

Table 1. Monthly average temperature and total precipitation for 2021 and 2022, and 30-yr monthly temperature and rainfall averages in Geneva, NY, USA.

	Air temp[i]			Total rainfall			Relative humidity	
	2021	2022	30-yr avg	2021	2022	30-yr avg	2021	2022
Month	°C			mm			hr ≥90%	
May	14.1	16.3	14.4	56	32	78	126	166
June	21.7	19.4	19.4	66	117	84	105	106
July	21.1	22.1	21.7	142	19	94	306	238
August	23.1	22.3	21.1	127	25	86	294	107
Total	—	—	—	391	193	342	831	617

[i] Data were obtained from a permanent, on-site weather station located at Cornell AgriTech.

volume ranging from 94 to 187 L·ha^{-1} when sugar beets reached a minimum of six true leaves.

Data collection. In 2021, weed cover, a visual estimate of the percentage of the total plot area covered with weeds, was assessed using a scale ranging from 0% (indicating no weed cover) to 100% (plots completely covered by weeds); ratings were performed at 1 and 3 weeks after POST treatments (WAT) and again at red beet harvest. In 2021, control of Powell amaranth (*Amaranthus powellii* S. Wats.) and common ragweed (*Ambrosia artemesiifolia* L.), the two most common species that escape the PRE herbicide program, was also evaluated at the whole plot level using a scale ranging from 0% (no weed control) to 100% (complete weed control compared with the control plots). In 2022, residual and early POST herbicides combined with below-average precipitation following May planting effectively suppressed weed emergence and establishment; therefore, cover and control ratings were not collected.

In 2021 and 2022, crop injury in response to acifluorfen, which was characterized by necrosis ("leaf loss"), discoloration ("bronzing"), and stunting, was visually rated using a scale ranging from 0% (no observed injury) to 100% (crop death) at 1 WAT, 3 WAT, and harvest. In 2021, *Popillia* beetles (*Popillia japonica* Newman, 1841), formerly referred to as Japanese beetles, infested the trial late in the season, although the degree of damage differed among acifluorfen treatments. As a result, a single plot-level rating of *Popillia* beetle damage was recorded at harvest using a scale of 0 to 5: 0, no feeding; 1, 1% to 20% leaf loss; 2, 21% to 40%; 3, 41% to 60%; 4, 61% to 80%; and 5, 81% to 100% leaf loss.

Significant rainfall in Jul and Aug 2021 (approximately 50% above the 30-year average) necessitated an early red beet harvest (64 DAS) to mitigate the risk of crop loss from waterlogging and disease. Red beets were hand-dug from two 1-m sections of row in the center of each plot and counted, and the foliage and roots were separated and weighed. Leaf biomass is not typically included in standard harvest metrics because it is not a primary yield component. However, because of the extreme weather conditions during the growing season, the authors chose to record leaf biomass to capture a more complete picture of crop growth and performance. In 2022, red beet harvest occurred on 2 Aug at the Hall location and on 10 Aug at Cornell AgriTech at 84 DAS and 86 DAS, respectively; these timings coincided with the start of commercial harvest operations at the Hall site. As in 2021, red beets were hand-dug from two 1-m sections of row in the center of each plot. The number and weights of small to medium beet (crown diameter, 1.9–6.4 cm) roots were recorded because these grades are preferred for canning and jarring (US Department of Agriculture 2016).

Data analysis. All statistical analyses were conducted using the generalized linear mixed model (GLIMMIX) procedure in SAS software (version 9.4; SAS Institute, Cary, NC, USA). Crop injury data collected in 2021 and 2022 were combined across years and locations (hereafter referred to as "environment"). Herbicide rate, application timing, and their interaction were considered fixed effects, while environment and replication nested within environment were designated

Table 2. Environmental conditions at the time of acifluorfen application for 'Ruby Queen' red beet studies conducted at Cornell AgriTech and at a commercial farm at Hall, NY, USA, in 2021 and 2022.

	2021		2022			
	Cornell AgriTech		Hall		Cornell AgriTech	
	6- to 8-leaf	10- to 12-leaf	6- to 8-leaf	10- to 12-leaf	6- to 8-leaf	10- to 12-leaf
Crop planting date	10 Jun		10 May		16 May	
Application date	9 Jul	21 Jul	11 Jun	29 Jun	15 Jun	7 Jul
Days after seeding	29	41	32	50	30	52
Air temperature (°C)	23.8	19.4	23.8	27.9	28.0	22.1
Relative humidity (%)	74	62	50	43	43	57
Wind speed (km·h^{-1})	4.8	12.8	2.1	2.7	6.9	5.6
Dew	No	No	No	No	No	No
Weed cover (%)	5–20	30–40	—	—	—	—
Weed size (cm)	1–5	10–20	—	—	—	—

as random effects in the model. Because of unfavorable weather conditions that affected crop growth and development in 2021, red beets were harvested at an earlier maturity stage in 2021 than in 2022. Consequently, yield was analyzed by year and expressed as a percentage of the control to maintain the factorial structure during the statistical analysis. The same model was used to analyze weed cover and control ratings. Because of unequal variance, weed control and crop injury data were converted using the arcsine square root transformation before the ANOVA and back-transformed for presentation purposes (Grafen and Hails 2002). When main effect interactions were not significant, data were combined over fixed effects. Mean comparisons for the fixed effects were performed using Tukey's honestly significant difference test when F values were statistically significant ($P \leq 0.05$).

Results and discussion

Weed cover and control. In 2021, all acifluorfen treatments significantly reduced whole plot weed cover relative to the control, although no statistical differences were observed among the acifluorfen treatments themselves (data not shown). Averaged over rates and timings, weed cover rates in acifluorfen-treated plots were 16% and 24% at 1 WAT and 3 WAT, respectively. In contrast, weed cover rates in the control averaged 37% and 84% for the same observation dates, respectively. By harvest, weed cover in the control had increased to 90%, but it only ranged from 15% with 0.28 kg·ha^{-1} a.i. applied POST at the 6- to 8-leaf stage of red beet development to 33% with 0.07 kg·ha^{-1} a.i. applied at the 10- to 12-leaf stage in the acifluorfen-treated plots. These two acifluorfen treatments were the only ones that exhibited significant differences in weed cover throughout the trial (data not shown).

Powell amaranth control was significantly influenced by application rate and timing (Table 3), but not by the interaction between the two main effects. Averaged across the early and later application timings, acifluorfen at 0.28 kg·ha^{-1} a.i. provided 96%, 89%, and 86% control of Powell amaranth at 1 WAT, 3 WAT, and harvest, respectively. Powell amaranth control with 0.14 kg·ha^{-1} a.i. acifluorfen ranged from 89% at 1 WAT to 81% at harvest. Significantly lower levels of control (68%–82%) were observed across all rating dates when acifluorfen was applied at the lowest rate of 0.07 kg·ha^{-1} a.i. When averaged across all acifluorfen rates, applications made during the 6- to 8-leaf red beet development stage provided superior Powell amaranth control at both 1 WAT (94%) and 3 WAT (87%) compared with applications made at the 10- to 12-leaf stage (84% and 79%). At harvest, Powell amaranth control did not differ between the two application timings, with a mean control rating of 78%.

Previous field studies have shown 81% to 96% control of Palmer amaranth, redroot pigweed (*Amaranthus retroflexus* L.), tumble pigweed (*Amaranthus albus* L.), and waterhemp 21 d after a POST application of acifluorfen at 0.28 kg·ha^{-1} a.i. (Mayo et al. 1995; Sweat et al. 1998). Bishop et al. (1996) reported that acifluorfen applied at 0.45 kg·ha^{-1} a.i. at the two-leaf growth stage of Powell amaranth provided complete control of the species in green beans. Split applications of 0.22 kg·ha^{-1} a.i. at both the two- and four-leaf stages of Powell amaranth development were also effective. Peters et al. (2021, 2022, 2023) found that acifluorfen at 0.28 kg·ha^{-1} a.i. effectively controlled waterhemp, with the ideal timing for control occurring when plants had a height less than 5 to 10 cm. Recent studies from Ontario suggest that acifluorfen provided only 64% and 37% control of Powell amaranth at 2 WAT and 4 WAT, respectively, following a POST application at 0.60 kg·ha^{-1} a.i. (Aicklen et al. 2022). Reduced efficacy against Powell amaranth in Ontario likely resulted from acifluorfen applications to plants with 6 to 13 leaves, exceeding the optimal growth stage for treatment. In the 2021 trial, Powell amaranth was less than 5 cm tall when red beets were at the 6- to 8-leaf developmental stage. Conversely, Powell amaranth reached 10 to 20 cm in height when red beets were at the 10- to 12-leaf stage of development, which likely resulted in the lower levels of control observed for the later application timing. Furthermore, continued Powell amaranth emergence following the breakdown of plant residual herbicides also contributed to the reductions in control observed over time. Unlike waterhemp, Palmer amaranth, and redroot pigweed, which developed PPO inhibitor resistance in the United States in 2001, 2011, and 2022, respectively (Heap 2025), resistance to PPO-inhibiting herbicides has not been confirmed in Powell amaranth.

The management of common ragweed was also significantly affected by application rate and timing (Table 3), although the control levels were considerably lower than those observed for Powell amaranth. When averaged across application timings, the 0.28 kg·ha^{-1} a.i. rate provided 50%, 34%, and 22% control of common ragweed at 1 WAT, 3 WAT, and harvest, respectively. The 0.14 kg·ha^{-1} a.i. rate resulted in 46% control at 1 WAT, but decreased to 20% by harvest. The lowest tested rate (0.07 kg·ha^{-1} a.i.) provided the least control of common ragweed, ranging from 16% to 40%. Like Powell amaranth, common ragweed control was greater at 1 WAT and 3 WAT (48% and 40%, respectively) when acifluorfen was applied at the 6- to 8-leaf red beet stage of development compared with the 10- to 12-leaf stage (43% and 18%). At harvest, common ragweed control did not differ between the two application timings, with an average control rating of 18%.

Poor common ragweed control compared with Powell amaranth may be attributed to the limited efficacy of PRE applications of *S*-metolachlor and ethofumesate against ragweed, as well as its earlier emergence and more advanced growth stage at the time of acifluorfen application. For example, while most weeds across the trial site were 1 to 5 cm tall at the early application timing and 10 to 20 cm tall at the later application timing, some common ragweed plants exceeded these heights, likely leading to reduced management success (Sosnoskie LM, personal observation). Ritter and Coble (1984) demonstrated ≥92% control of common ragweed 2 WAT with acifluorfen at 0.40 or 0.60 kg·ha^{-1} a.i. applied to 2- to 4-week-old plants, but only 72% and 30% control when applied to 6- and 8-week-old plants, respectively. Lee and Oliver (1982) reported ≥85% control of velvetleaf (*Abutilon theophrasti* Medik.), entireleaf morningglory (*Ipomoea hederacea* Jacq.), and common cocklebur at 2 WAT when acifluorfen was applied at 0.30 kg·ha^{-1} a.i. to weeds at the two-leaf stage. However, control dropped to ≤30% when

Table 3. Powell amaranth (*Amaranthus powellii*) and common ragweed (*Ambrosia artemisiifolia*) control in response to acifluorfen rate and timing of application at Cornell AgriTech, NY, USA, in 2021.

	Powell amaranth			Common ragweed		
	1 WAT[ii]	3 WAT	Harvest	1 WAT	3 WAT	Harvest
Treatment	% of UTC					
Acifluorfen rate (kg·ha^{-1} a.i.)[i]						
0.07	82[iii] c	74 b	68 c	40 b	24 b	16 b
0.14	89 b	85 a	81 b	46 ab	29 ab	20 ab
0.28	96 a	89 a	86 a	50 a	34 a	22 a
P	<0.0001	<0.0001	<0.0001	0.0091	0.0030	0.0356
Crop stage						
6- to 8-leaf[ii]	94 a	87 a	77	48 a	40 a	20
10- to 12-leaf	84 b	79 b	79	43 b	18 b	18
P	<0.0001	<0.0001	0.2039	0.0447	<0.0001	0.2162

[i] 1 kg·ha^{-1} = 0.8921 lb/acre.
[ii] 6- to 8-leaf and 10- to 12-leaf applications were made on 9 and 21 Jul 2021, respectively.
[iii] Means followed by the same letter in a column are not significantly different based on Tukey's honestly significant difference test (α = 0.05). Data from control plots were not included in the analysis.
UTC = control not treated with acifluorfen; WAT = weeks after treatment.

the same treatment was applied at the 6- to 8-leaf stage.

Crop injury. Necrosis data were only collected in 2021, because no substantial leaf injury occurred in 2022. Red beet crop injury was significantly influenced by both acifluorfen rate and application timing (Table 4), but not their interaction. Leaf necrosis severity increased with the acifluorfen rate, with 0.28 kg·ha^{-1} a.i. causing significantly greater leaf loss (46%, 31%, and 12% at 1 WAT, 3 WAT, and harvest, respectively) compared with 0.14 kg·ha^{-1} a.i. (35%, 29%, and 9%) and 0.07 kg·ha^{-1} a.i. (26%, 23%, and 8%). Application timing also affected necrotic injury, with applications at the earlier 6- to 8-leaf stage causing more damage (58%, 48%, and 19% at 1 WAT, 3 WAT, and harvest, respectively) than those at the 10- to 12-leaf stage (13%, 8%, and 0%).

Similar patterns emerged for the leaf discoloration symptoms. Injury increased with the application rate. At 1 WAT, discoloration was 45%, 35%, and 27% for the 0.28, 0.14, and 0.07 kg·ha^{-1} a.i. acifluorfen rates, respectively. At 3 WAT, discoloration decreased to 23%, 19%, and 15%, respectively. By harvest, discoloration ranged from 4% (0.07 kg·ha^{-1} a.i.) to 7% (0.28 kg·ha^{-1} a.i.). Early application (6- to 8-leaf stage) resulted in significantly more leaf discoloration at 1 WAT (47%) compared with application at the 10- to 12-leaf stage (21%). Discoloration at 3 WAT was not significantly affected by application timing. At harvest, the pattern reversed, with later applications showing slightly more leaf discoloration (7%) than earlier applications (4%).

Environmental conditions significantly influence injury severity from PPO-inhibiting herbicides. Lower RH during application in 2022 compared with that in 2021, particularly at the 6- to 8-leaf stage, may explain the absence of necrosis in response to acifluorfen. Within 72 h of the 6- to 8-leaf stage application, RH ≥90% totaled 41 h in 2021 compared with no more than 12 h in 2022. Studies by Ritter and Coble (1981) and Wichert et al.

Table 4. 'Ruby Queen' red beet leaf necrosis and discoloration in response to the acifluorfen rate and timing of application at Cornell AgriTech, NY, USA, in 2021 and 2022, and Hall, NY, USA, in 2022.

	Necrosis[ii]			Discoloration		
	1 WAT	3 WAT	Harvest	1 WAT	3 WAT	Harvest
Treatment	% of UTC					
Acifluorfen rate (kg·ha^{-1} a.i.)[i]						
0.07	26[iv] c	23 b	8 b	27 b	15 b	4 b
0.14	35 b	29 a	9 ab	35 ab	19 ab	6 ab
0.28	46 a	31 a	12 a	45 a	23 a	7 a
P	<0.0001	0.0088	0.0416	0.0006	0.0004	0.0325
Crop stage						
6- to 8-leaf[iii]	58 a	48 a	19 a	47 a	20	4 b
10- to 12-leaf	13 b	8 b	0 b	21 b	18	7 a
P	<0.0001	<0.0001	<0.0001	<0.0001	0.1260	0.0005

[i] 1 kg·ha^{-1} = 0.8921 lb/acre.
[ii] Necrosis data reported are for 2021 only because no necrosis was observed in 2022.
[iii] 6- and 8-leaf and 10- and 12-leaf applications were made on 9 and 21 Jul 2021, respectively, on 11 Jun (Hall) and 15 Jun 2022 (Cornell AgriTech), and on 29 Jun (Hall) and 5 Jul 2022 (Cornell AgriTech), respectively.
[iv] Means followed by the same letter in a column are not significantly different based on based on Tukey's honestly significant difference test (α = 0.05). Data from control plots were not included in the analysis.
UTC = control not treated with acifluorfen; WAT = weeks after treatment.

(1992) demonstrated that RH affects acifluorfen weed control performance, with higher humidity enhancing injury potential. Ritter and Coble (1981) found that acifluorfen applied at 0.30 or 0.60 kg·ha^{-1} a.i. caused greater dry weight reduction in common cocklebur and common ragweed under high (85%) RH than under low (50%) RH; using ^{14}C-labeled acifluorfen, they demonstrated higher absorption and translocation in common cocklebur 2 WAT under high RH compared with that under low RH, with diurnal/nocturnal temperatures of 32 °C/22 °C. Wichert et al. (1992) found that decreasing RH from 85% to 50% reduced acifluorfen (0.28 or 0.56 kg·ha^{-1} a.i.) efficacy on pitted morningglory (*Ipomoea lacunosa* L.) and entireleaf morningglory 2 WAT, with control rates of 52% and 34%, respectively, compared with 93% and 69%, respectively, under high RH. Similarly, acifluorfen at 0.10 kg·ha^{-1} a.i. was less toxic to showy crotalaria (*Crotalaria spectabilis* Roth) at 40% RH than at 100%, and at 18 °C than at 27 °C or 35 °C (Wills and McWhorter, 1981).

Crop stunting. Red beet stunting following acifluorfen application was significantly affected by both application rate and timing (Table 5), but not their interaction. Stunting severity increased with the acifluorfen rate, with 0.28 kg·ha^{-1} a.i. causing significantly more injury at 1 WAT (34%) compared with 0.14 kg·ha^{-1} a.i. (22%) and 0.07 kg·ha^{-1} a.i. (18%). This pattern persisted at 3 WAT, with stunting of 26%, 18%, and 10% for the 0.28, 0.14, and 0.07 kg·ha^{-1} a.i. rates, respectively. By harvest, differences among rates were no longer significant, with stunting ranging from 4% to 6%. Application timing also affected stunting. Applications at the 6- to 8-leaf stage resulted in more injury (42%, 30%, and 10% at 1 WAT, 3 WAT, and harvest, respectively) than applications at the 10- to 12-leaf stage (7%, 6%, and 1%, respectively).

The longer crop growing period in 2022, with harvest occurring 20 d later than that in 2021, likely provided red beets with additional time to recover from acifluorfen-caused damage. This extended recovery period may explain why damage symptoms observed earlier in the season were no longer apparent at harvest in 2022. Boyer et al. (2011) reported that peanut crops recovered completely from foliar necrosis 28 d after treatment, but canopy closure was delayed by 10 d when acifluorfen (0.42 kg·ha^{-1} a.i.) or lactofen (0.21 kg·ha^{-1} a.i.) was applied 4 weeks after planting. Applications at 8 or 10 weeks after planting resulted in delays of only 3 d or less. Similarly, acifluorfen applied at 0.56 kg·ha^{-1} a.i. to soybean at the V2 stage (28 d after planting) caused 14% crop injury 2 WAT and delayed soybean reaching 80% groundcover by 5 d compared with a nontreated weed-free control (Priess et al. 2020). Although the delay in soybean canopy closure did not impact yield, the authors hypothesized that delayed groundcover allows sunlight to reach the soil surface longer during the growing season, potentially promoting late-season weed germination and necessitating an additional POST herbicide application.

Table 5. 'Ruby Queen' red beet stunting in response to acifluorfen rate and timing of application at Cornell AgriTech, Geneva, NY, USA, in 2021 and 2022, and Hall, NY, USA, in 2022.

	1 WAT	3 WAT	Harvest
Treatment		% of UTC	
Acifluorfen rate (kg·ha^{-1} a.i.)[i]			
0.07	18[iii] b	10 c	4
0.14	22 b	18 b	6
0.28	34 a	26 a	6
P	<0.0001	<0.0001	0.4298
Crop stage			
6- to 8-leaf[ii]	42 a	30 a	10 a
10- to 12-leaf	7 b	6 b	1 b
P	<0.0001	<0.0001	<0.0001

[i] 1 kg·ha^{-1} = 0.8921 lb/acre.
[ii] 6- to 8-leaf and 10- to 12-leaf applications were made on 9 and 21 Jul 2021, respectively, on 11 Jun (Hall) and 15 Jun 2022 (Cornell AgriTech), and on 29 Jun (Hall) and 5 Jul 2022 (Cornell AgriTech), respectively.
[iii] Means followed by the same letter in a column are not significantly different based on Tukey's honestly significant difference test (α = 0.05). Data from control plots were not included in the analysis.
UTC = control not treated with acifluorfen; WAT = weeks after treatment.

Crop leaf biomass root yield. Leaf biomass data, which were only collected in 2021, showed no significant differences among acifluorfen rates (Table 6), with values ranging from 73% of the control at the lowest rate tested (0.07 kg·ha^{-1} a.i.) to 62% at the highest rate (0.28 kg·ha^{-1} a.i.). Conversely, application timing had a substantial impact on leaf biomass, with applications at the early growth stage (6- to 8-leaf stage) resulting in significantly reduced leaf biomass (47% of the control) compared with applications at the 10- to 12-leaf stage (89% of the control). Reductions in leaf biomass accumulation at harvest following acifluorfen applications at the6- to 8-leaf red beet stage of development were directly related to herbicide damage, which resulted in leaf loss and crop stunting. This damage was exacerbated by prevailing weather conditions. In contrast, direct herbicide injury was less severe for applications made at the 10- to 12-leaf stage; however, subsequent *Popillia* beetle infestation likely influenced leaf biomass measurements at harvest. In 2021, *Popillia* beetles infested the research farm late in the season, following acifluorfen applications at the 10- to 12-leaf stage (Fig. 1). Differential injury was observed across the trial. The severity of red beet injury was not correlated with the herbicide application rate, but it was significantly influenced by the application timing (data not shown). Feeding damage was most severe in recently treated red beets (10- to 12-leaf application timing), with injury ratings ranging from 2.4 to 2.6 on our assessment scale. In contrast, plots treated earlier at the 6- to 8-leaf stage exhibited significantly less insect damage, with ratings ranging from 0.5 to 0.75. The control had a comparable injury rating of 0.6. The mechanisms facilitating *Popillia* herbivory at the 10- to 12-leaf stage are unknown.

Vigorous beet foliage is essential for supporting beet root development. Herbicide-induced leaf tissue loss can inhibit root development as plants redirect resources toward regenerating aboveground biomass. With respect to red beet root biomass, applications of acifluorfen at the 6- to 8-leaf stage

Table 6. **'Ruby Queen' red beet leaf and total root biomass at harvest in response to acifluorfen rate and timing of application at Cornell AgriTech, NY, USA, in 2021 and 2022, and Hall, NY, USA, in 2022.**

		Total root yield	
	Leaf biomass[ii]	2021	2022
Treatment	% of UTC[iii]		
Acifluorfen rate (kg·ha^{-1} a.i.)[i]			
0.07	73	53	92
0.14	68	48	84
0.28	62	49	81
P	0.2488	0.6331	0.2869
Crop stage			
6- to 8-leaf[iv]	47[v] b	27 b	80 b
10- to 12-leaf	89 a	72 a	91 a
P	<0.0001	<0.0001	0.0412

[i] 1 kg·ha^{-1} = 0.8921 lb/acre.

[ii] Leaf biomass data reported are for 2021 only because no data were collected in 2022.

[iii] UTC refers to the control not treated with acifluorfen. UTC leaf biomass and root yield in 2021 were 2.43 and 1.38 kg·m^{-1} of the row, respectively, while root yield in 2022 averaged 4.36 kg·m^{-1} of the row.

[iv] 6- to 8-leaf and 10- to 12-leaf applications were made on 9 and 21 Jul 2021, respectively, 11 Jun (Hall) and 15 Jun 2022 (Cornell AgriTech), and 29 Jun (Hall) and 5 Jul 2022 (Cornell AgriTech), respectively.

[v] Means followed by the same letter in a column are not significantly different based on Tukey's honestly significant difference test (α = 0.05).

resulted in significantly lower yields (−72% relative to the control) compared with applications at the 10- to 12-leaf stage (−28%) in 2021. The same trend was observed for 2022, although the impacts of acifluorfen applications on root yields were not as severe. In 2022, applications at the 6- to 8-leaf stage caused greater biomass reduction (−20% relative to the control) than applications at the 10- to 12-leaf stage (−9%). The unfavorable weather conditions in 2021 necessitated harvesting beets 20 d earlier than in 2022 relative to seeding date. This shortened growing period likely limited recovery time from the greater acifluorfen-induced foliage injury when applied at the 6- to 8-leaf stage. In contrast, the extended growing period in 2022 may have allowed sufficient time for plants to recover from injury, particularly because no leaf necrosis was observed in 2022.

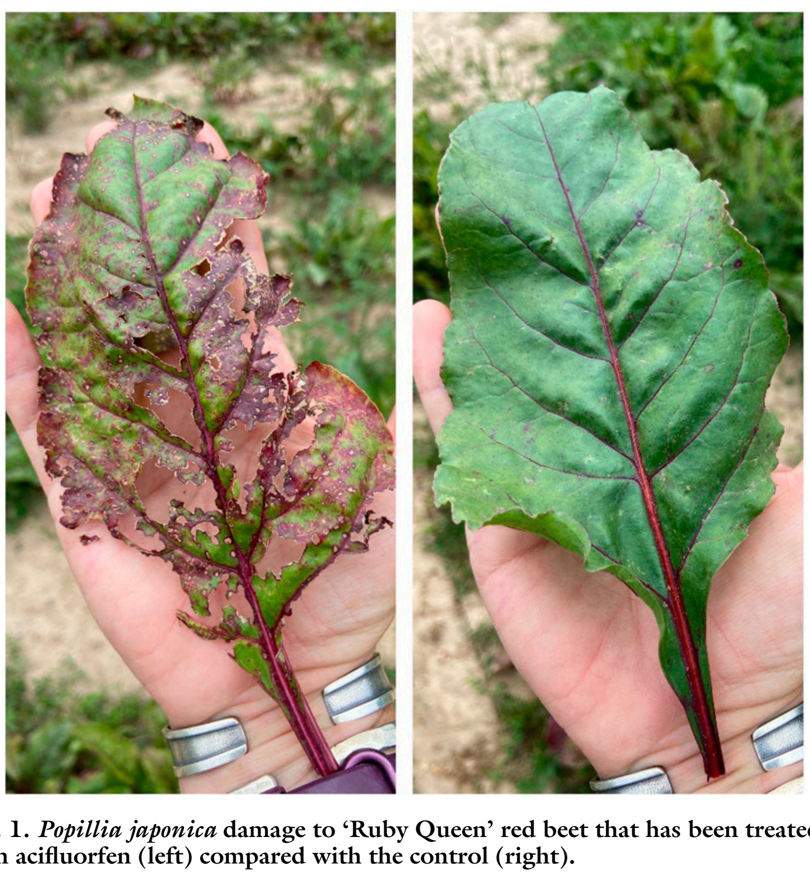

Fig. 1. ***Popillia japonica*** **damage to 'Ruby Queen' red beet that has been treated with acifluorfen (left) compared with the control (right).**

Weed management in red beet production is challenged by a limited number of herbicide options, most with narrow control spectra, requiring multiple POST applications at reduced rates to ensure crop safety. The currently registered POST herbicides provide inadequate control of pigweeds, which are particularly problematic weed species. While PRE herbicides like cycloate and *S*-metolachlor provide some suppression, their efficacy is short-lived, necessitating additional in-season control. Acifluorfen, a PPO inhibitor, has shown promise for POST pigweed control in sugar beets and is currently used under Section 18 Emergency Exemptions in several states. However, its potential for crop injury, especially when applied at earlier growth stages, warrants careful evaluation. This study aimed to assess the efficacy and crop safety of acifluorfen in red beet production, with results showing that although red beets can recover from early-season stunting, applications at the 10- to 12-leaf stage at rates up to 0.28 kg·ha^{-1} a.i. cause less crop damage while maintaining effective (>80%) pigweed control. These later applications may provide a safer option for integrating acifluorfen into red beet weed management programs. However, growing conditions across study years strongly influenced acifluorfen safety in red beet. In 2021, above-average rainfall created stress conditions that increased acifluorfen injury and inhibited red beet recovery, particularly in plots treated at the 6- to 8-leaf growth stage, resulting in significant yield reductions. In contrast, more favorable growing conditions in 2022 allowed for improved crop recovery, resulting in noticeably reduced injury symptoms and minimal yield losses. Our trial demonstrated effective control of Powell amaranth using acifluorfen; however, common ragweed was poorly managed. To fully understand the utility of acifluorfen in red beet production, further evaluation under a broader spectrum of weed species is necessary. Additionally, more research is necessary to better characterize the environmental conditions that influence crop vigor and recovery potential following herbicide application.

References cited

Aicklen IK, Soltani N, Tardif FJ, Robinson DE, Laforest M, Sikkema PH. 2022. Control of multiple-herbicide-resistant green pigweed (*Amaranthus powellii*) with preemergence and postemergence herbicides in Ontario soybean production. Agronomy. 12(9):2075. https://doi.org/10.3390/agronomy12092075.

Barrentine WL. 1978. Broadleaf weed control in soybeans with acifluorfen. Proc South Weed Sci Soc. 31:313.

Beiermann CW, Creech CF, Knezevic SZ, Jhala AJ, Harveson R, Lawrence NC. 2021. Response of Palmer amaranth (*Amaranthus palmeri* S. Watson) and sugarbeet to desmedipham and phenmedipham. Weed Technol. 35(3):440–448. https://doi.org/10.1017/wet.2021.1.

Bishop C, Pemberton BM, Stagg J. 1996. Control of *amaranthus* (*Amaranthus powellii)* in green bean crops. Eleventh Australian Weeds Conference Proceedings. 138-140.

Boyer JA, Ferrell J, MacDonald G, Tillman B, Rowland D. 2011. Effect of acifluorfen and lactofen application timing on peanut injury and yield. Crop Manag. 10(1):1–6. https://doi.org/10.1094/CM-2011-0519-01-RS.

Carvalho LB, Guzzo CD, Pitelli RA, Cecílio Filho AB, Bianco S. 2010. The effects of the coexistence of weed communities on table beet yield during early crop development. Acta Sci Agron. 32(4): 709–714. https://doi.org/10.4025/actasciagron.v32i4.4649.

Chancia R, van Aardt J, Pethybridge S, Cross D, Henderson J. 2021. Predicting table beet root yield with multispectral UAS imagery. Remote Sensing. 13(11):2180. https://doi.org/10.3390/rs13112180.

Colquhoun JB, Heider DJ, Rittmeyer RA. 2016. Evaluation of season-long weed management programs in red beet. Weed Technol. 30(4):898–909. https://doi.org/10.1614/WT-D-16-00015.1.

D'Egidio S, Galieni A, Stagnari F, Pagnani G, Pisante M. 2019. Yield, quality and physiological traits of red beet under different magnesium nutrition and light intensity levels. Agronomy. 9(7):379. https://doi.org/10.3390/agronomy9070379.

Gossett BJ, Toler JE. 1999. Differential control of Palmer amaranth (*Amaranthus palmeri*) and smooth pigweed (*Amaranthus hybridus*) by postemergence herbicides in soybean (*Glycine max*). Weed Technol. 13(1):165–168. https://doi.org/10.1017/S0890037X00045085.

Grafen A, Hails R. 2002. Modern statistics for the life sciences. Oxford University Press, New York, NY, USA.

Heap I. 2025. The International Herbicide-Resistant Weed Database. https://www.weedscience.org/Home.aspx. [accessed 31 Mar 2025].

Hewson RT, Roberts HA. 1973. Effects of weed competition for different periods on the growth and yield of red beet. J Hortic Sci. 48(3):281–292. https://doi.org/10.1080/00221589.1973.11514530.

Kavaliauskaitė D, Bobinas Č. 2006. Determination of weed competition critical period in red beet. Agron Res. 4:217–220.

Kemp NJ, Taylor EC, Renner KA. 2009. Weed management in glyphosate-and glufosinate-resistant sugar beet. Weed Technol. 23(3):416–424. https://doi.org/10.1614/WT-07-114.1.

Khan MF. 2010. Introduction of glyphosate-tolerant sugar beet in the United States. Outlook Pest Man. 21(1):38–41. https://doi.org/10.1564/21feb10.

Kikkert JR, Reiners S, Gugino BK. 2010. Row width, population density, and harvest date effects on marketable yield of table beet. HortTechnology. 20(3): 560–567. https://doi.org/10.21273/HORTTECH.20.3.560.

Kniss AR, Wilson RG, Martin AR, Burgener PA, Feuz DM. 2004. Economic evaluation of glyphosate-resistant and conventional sugar beet. Weed Technol. 18(2):388–396. https://doi.org/10.1614/WT-03-119R.

Kołota E, Osińska M. 1998. Studies on the susceptibility of red-beet to weed infestation, with respect to the possibility of reduced herbicides use. Roczniki Akademii Rolniczej w Poznaniu Ogrodnictwo. 27:159–164.

Lee SD, Oliver LR. 1982. Efficacy of acifluorfen on broadleaf weeds. Times and methods for application. Weed Sci. 30(5):520–526. https://doi.org/10.1017/S0043174500041096.

Mayo CM, Horak MJ, Peterson DE, Boyer JE. 1995. Differential control of four Amaranthus species by six postemergence herbicides in soybean (*Glycine max*). Weed Technol. 9(1):141–147. https://doi.org/10.1017/S0890037X00023083.

Morishita DW. 2018. Impact of glyphosate-resistant sugar beet. Pest Manag Sci. 74(5):1050–1053. https://doi.org/10.1002/ps.4503.

Oliver LR, Howe OW. 1980. Jimsonweed control in soybeans. Ark Farm Res. 26(2):2.

Peters TJ, Lystad AL, Mettler D. 2021. Sugar beet tolerance and waterhemp control from Ultra Blazer in a weed management program. https://www.sbreb.org/wp-content/uploads/2024/02/Sugar beet-tolerance-and-waterhemp-control-from-Ultra-Blazer.Final_.pdf. [accessed 26 Jul 2024].

Peters TJ, Lystad AL, Burt E, Mettler D. 2022. Sugar beet tolerance from Ultra Blazer. https://www.sbreb.org/wp-content/uploads/2024/03/SUGAR BEET-TOLERANCE-FROM-ULTRA-BLAZER.Final_.pdf. [accessed 26 Jul 2024].

Peters TJ, Lystad AL, Burt E, Mettler D. 2023. Summary of Ultra Blazer applied in sugar beet. https://www.sbreb.org/wp-content/uploads/2024/04/SUMMARY-OF-ULTRA-BLAZER-APPLIED-IN-SUGAR BEET.pdf. [accessed 26 Jul 2024].

Pethybridge SJ, Kikkert JR, Hanson LE, Nelson SC. 2018. Challenges and prospects for building resilient disease management strategies and tactics for the New York table beet industry. Agronomy. 8(7):112. https://doi.org/10.3390/agronomy8070112.

Priess GL, Norsworthy JK, Roberts TL, Gbur EE. 2020. Impact of postemergence herbicides on soybean injury and canopy formation. Weed Technol. 34(5): 727–734. https://doi.org/10.1017/wet.2020.55.

Ritter DL, Coble HD. 1981. Influence of temperature and relative humidity on the activity of acifluorfen. Weed Sci. 29(4): 480–485. https://doi.org/10.1017/S0043174500040030.

Ritter RL, Coble HD. 1984. Influence of crop canopy, weed maturity, and rainfall on acifluorfen activity. Weed Sci. 32(2): 185–190. https://doi.org/10.1017/S004317450005877X.

Robinson DE, McNaughton KE, Bilyea D. 2013. Comparison of sequential preemergence-postemergence and postemergence-alone weed management strategies for red beet (*Beta vulgaris* L.). Can J Plant Sci. 93(5):863–870. https://doi.org/10.4141/cjps2012-327.

Sperry BP, Ferrell JA, Smith HC, Fernandez VJ, Leon RG, Smith CA. 2017. Effect of sequential applications of protoporphyrinogen oxidase-inhibiting herbicides on Palmer amaranth (*Amaranthus palmeri*) control and peanut response. Weed Technol. 31(1): 46–52. https://doi.org/10.1017/wet.2016.3.

Stivers L. 1999. Crop profile: Beets in New York. Cornell Cooperative Extension Bulletin. http://pmep.cce.cornell.edu/fqpa/crop-profiles/beet.html. [accessed 25 Mar 2025].

Sweat JK, Horak MJ, Peterson DE, Lloyd RW, Boyer JE. 1998. Herbicide efficacy on four amaranthus species in soybean (*Glycine max*). Weed Technol. 12(2): 315–321. https://doi.org/10.1017/S0890037X00043876.

United Phosphorus Limited. 2023. Ultra Blazer® herbicide label. https://www.cdms.net/ldat/ld3LJ014.pdf. [accessed 28 May 2025].

US Department of Agriculture. 2016. United States Standards for Grades of Beets. https://www.ams.usda.gov/sites/default/files/media/BeetsStandard.pdf. [accessed 12 Mar 2025].

US Department of Agriculture-National Agricultural Statistic Service. 2025. Quick Stats. https://quickstats.nass.usda.gov/results/A1CFAB13-B0F7-31E7-9CB6-D9AF33B8C263. [accessed 12 Mar 2025].

US Environmental Protection Agency. 2025. Pesticide Emergency Exemptions. https://www.epa.gov/pesticide-registration/pesticide-emergency-exemptions. [accessed 31 Mar 2025].

Wichert RA, Bozsa R, Talbert RE, Oliver LR. 1992. Temperature and relative humidity effects on diphenylether herbicides. Weed Technol. 6(1):19–24. https://doi.org/10.1017/S0890037X00034230.

Wills GD, McWhorter CG. 1981. Effect of environment on the translocation and toxicity of acifluorfen to showy crotalaria (*Crotalaria spectabilis*). Weed Sci. 29(4):397–401. https://doi.org/10.1017/S0043174500039886.

Wilson RG, Sbatella GM. 2011. Late-season weed control in glyphosate-resistant sugarbeet. Weed Technol. 25(3):350–355. https://doi.org/10.1614/WT-D-10-00057.1.