Weed Research

WILEY

ORIGINAL ARTICLE OPEN ACCESS

Florpyrauxifen-Benzyl Controls *Cirsium arvense* by Inhibiting Root Growth and Decreasing Root Bud Regeneration

Joshua W. A. Miranda[1,2] | Marcelo L. Moretti[2]

[1]Department of Horticulture, Michigan State University, East Lansing, Michigan, USA | [2]Department of Horticulture, Oregon State University, Corvallis, Oregon, USA

Correspondence: Joshua W. A. Miranda (miran101@msu.edu)

Received: 4 September 2025 | **Revised:** 8 April 2026 | **Accepted:** 16 April 2026

Subject Editor: Graeme Bourdot

Keywords: perennial weed management | root biomass | synthetic auxin | vegetative regeneration

ABSTRACT

Cirsium arvense L. (Canada thistle) is a perennial weed with an extensive root system and prolific vegetative propagation through adventitious root buds, making long-term management challenging. Florpyrauxifen-benzyl, a novel synthetic auxin herbicide, has shown potential for controlling broadleaf weeds, but its effects on *C. arvense* root growth and regeneration are not documented. Greenhouse studies evaluated florpyrauxifen-benzyl at 9–38 g ai ha^{-1}, applied as single or sequential treatments at the rosette and bolting stages, measuring control, root biomass reduction, and root bud regeneration. A second greenhouse study compared florpyrauxifen-benzyl (29 g ha^{-1}) with glyphosate, clopyralid, 2,4-D, glufosinate, flazasulfuron, carfentrazone, and selected mixtures. Field studies evaluated florpyrauxifen-benzyl programs alone or in combination with mowing across three sites. In the greenhouse, florpyrauxifen-benzyl provided 86%–94% shoot control, reduced root biomass by ≥ 97% at the rosette stage and by ≥ 80% at the bolting stage, and lowered root bud regeneration to ≤ 14% of root segments, an effect comparable to that of glyphosate and clopyralid. In the field, sequential applications or mowing followed by florpyrauxifen-benzyl significantly improved control (73%–79%) compared to a single spring application (69%) or single summer application (30%). Mixtures of florpyrauxifen-benzyl with glufosinate or flazasulfuron did not improve control of *C. arvense*. Results indicate that florpyrauxifen-benzyl effectively controls *C. arvense* through reductions in root biomass and inhibition of vegetative regeneration, with performance comparable to industry standards. These results support its use in perennial cropping systems, where it can be integrated with practices such as mowing or sequential applications to improve season-long control and reduce flowering and seed production.

1 | Introduction

Cirsium arvense L. (Canada thistle) is a perennial broadleaf weed native to southeastern Europe and the eastern Mediterranean region (Morishita 1999). *C. arvense* thrives in temperate climates, infesting crops in areas of Africa, the Middle East, Asia, Oceania, and North and South America (Mitich 1988). Likely introduced to North America in the 1600s through contaminated crop seed or ship ballast, it has become a troublesome weed species, posing significant challenges to agriculture, pasturelands, and disturbed habitats worldwide (Foote et al. 1970; Hodgson 1970; Donald 1992; Beck and Sebastian 2000; Enloe et al. 2007; Davis et al. 2018). Its global spread underscores both its ecological adaptability and the persistent challenges it poses to weed management.

Cirsium arvense is particularly known for its rapid spread, extensive root system, and ability to propagate vegetatively from root

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.

© 2026 The Author(s). *Weed Research* published by John Wiley & Sons Ltd on behalf of European Weed Research Society.

buds, making it difficult to manage (Donald 1984; McAllister and Haderlie 1985a, 1985b; Carlson and Donald 1988). Root networks can exceed 5 m in depth and length, storing substantial carbohydrate reserves that sustain vegetative regeneration (Carlson and Donald 1988; Miller and Lym 1998; Tiley 2010; Sciegienka et al. 2011; Davis et al. 2018). Unlike annual weeds that rely primarily on seed production, *C. arvense* propagates clonally through adventitious buds located along its root system (Carlson and Donald 1988; Donald 1993; Ziska et al. 2004). Consequently, even after shoots are removed, new buds readily emerge from roots, re-establishing infestations (Carlson and Donald 1988; Donald 1993; Ziska et al. 2004). Its resilience, coupled with the weed's competitive ability, enables *C. arvense* to outcompete crops for water, light, and nutrients, often causing severe yield losses and long-term soil seedbank enrichment (Sciegienka et al. 2011; Davis et al. 2018).

Traditional management strategies for *C. arvense* have combined mechanical and chemical approaches, though both have significant limitations that restrict their effectiveness. Mechanical control methods such as mowing, cultivation, or tillage can temporarily reduce shoot growth or prevent seed production, but can also stimulate root bud development or spread root fragments, exacerbating infestations (Davis et al. 2018; Orloff et al. 2018). Conversely, strategic mowing regimes have been shown to suppress *C. arvense* populations over time and, under certain conditions, may contribute to long-term population decline (Bourdôt et al. 2016). Chemical control, particularly with systemic herbicides, has proven more effective against *C. arvense* because these herbicides can translocate to roots and inhibit vegetative regrowth (Davis et al. 2018). Glyphosate and auxinic herbicides such as clopyralid have long been used to effectively manage *C. arvense* (Carlson and Donald 1988; Baccin and Moretti 2024). Their efficacy is strongly influenced by application timing, growth stage, and environmental conditions, while crop selectivity, off-target injury, and the risk of herbicide resistance from repeated use remain major concerns (Hunter 1996; Peterson et al. 2018).

A promising herbicide for managing *C. arvense* is florpyrauxifen-benzyl, a novel synthetic auxin herbicide with a unique mechanism of action. Unlike many older auxin herbicides that act primarily through auxin receptor sites such as TIR1-mediated pathways, florpyrauxifen-benzyl is known to preferentially bind to the AFB5 receptor site, a different component of the SCFTIR/AFB protein complex (Prusinska et al. 2023; Wang et al. 2021). This unique target site provides an opportunity to diversify auxin herbicide use. Florpyrauxifen-benzyl is characterized by low volatility and high systemic activity, enabling in-season use without the drift concerns associated with other auxin-based herbicides (Miller and Norsworthy 2018a; Miranda and Moretti 2025). Although its effectiveness on controlling annual weeds is well documented, florpyrauxifen effects on perennial weeds is still unknown. Specifically, its ability to inhibit underground structures.

In this study, we evaluated the effects of florpyrauxifen-benzyl on *C. arvense*, focusing on shoot control, root biomass reduction, and inhibition of root bud regeneration. These responses capture both the immediate competitive effects of shoot growth and the long-term persistence driven by underground reserves and vegetative regrowth. Assessing them under greenhouse and field conditions allowed us to determine the potential of florpyrauxifen-benzyl as a tool for sustainable management of *C. arvense*.

2 | Materials and Methods

2.1 | Greenhouse Studies

Root fragments of *C. arvense* were collected from an organic experimental farm at Oregon State University (44.55, −123.21), segmented into 6- to 8-cm sections to promote regrowth, and transplanted into flat trays containing commercial potting mix (SS#4 PC RSi, Sun Gro Horticulture, Agawam, MA). Trays were maintained in a greenhouse at Oregon State University (44.57, −123.29), where day and night temperatures were set to 22°C and 18°C, respectively, and a 14 h photoperiod supplemented by artificial lighting. Two weeks after shoot emergence, plants were transplanted into individual 5-L pots filled with the same potting mix and grown under the same conditions.

The greenhouse research comprised two studies. The first study evaluated florpyrauxifen-benzyl (Hulk; Corteva Agriscience, Indianapolis, IN) applied at two growth stages of *C. arvense*. The second study evaluated florpyrauxifen-benzyl alone or in combination with currently registered herbicides in hazelnut. Treatments were applied using a research sprayer (DeVries Manufacturing Generation III, Hollandale, MN) equipped with a single TP8003E nozzle (TeeJet Technologies, Glendale Heights, IL), positioned 45 cm above the plant canopy and calibrated to deliver 187 L ha^{-1} of spray solution.

2.1.1 | Response of *C. arvense* to Florpyrauxifen-Benzyl

The first greenhouse study evaluated florpyrauxifen-benzyl applied at four rates (9, 18, 29, and 38 g ai ha^{-1}) to *C. arvense* at the rosette (8–10 leaf nodes, BBCH-18) and bolting (second fully extended internode, BBCH-32) stages. Treatments consisted of single applications at each rate or sequential applications [same rate followed by (fb) same rate, 28 days apart]. Treatments were arranged in a randomized complete block design (RCBD) with a factorial arrangement of growth stage × herbicide treatment, and four replications. The study was conducted twice. Fifty-six days after the initial treatment (DAIT), aboveground biomass was harvested, oven-dried, and weighed. Root systems were collected immediately after, washed to remove soil, gently dried and weighed fresh. Each root system was segmented into 10 5-cm sections and replanted into trays with potting mix, as previously described. After 35 days, segments were assessed for root bud regeneration (i.e., regrowth), with survival recorded as 1 (regenerated) or 0 (non-regenerated). For segments that regenerated, the number of secondary shoots arising from each segment was counted.

2.1.2 | Comparison With Other Herbicides

The second greenhouse study focused on the bolting growth stage (BBCH-32) of *C. arvense*. Treatments included florpyrauxifen-benzyl at 29 g ai ha^{-1} applied alone or in combination (+) with clopyralid (Stinger; Corteva Agriscience)

at 280 g ai ha^{-1}, glufosinate (Rely 280; BASF Corp., Research Triangle Park, NC) at 1150 g ai ha^{-1}, or flazasulfuron (Mission; Summit Agro, Durham, NC) at 200 g ai ha^{-1}. Standard herbicides were also evaluated individually: glyphosate (Roundup PowerMAX; Bayer CropScience, St. Louis, MO) at 1680 g ae ha^{-1}, 2,4-D (Sabre; Loveland Products, Loveland, CO) at 1060 g ae ha^{-1}, clopyralid at 280 g ai ha^{-1}, glufosinate at 1150 g ai ha^{-1}, flazasulfuron at 200 g ai ha^{-1}, and carfentrazone (Aim EC; FMC Corp., Philadelphia, PA) at 35 g ai ha^{-1}. Mowing (simulated by hand-clipping plants 1 cm aboveground) and a nontreated control were included for comparison. Treatments were arranged in an RCBD with four replications. The study was conducted twice. As in the first study, aboveground biomass was harvested, dried, and weighed at 56 DAIT. Root systems were processed as described above, and regrowth from 10 5-cm root segments was evaluated after 35 days to determine survival.

2.2 | Field Study

Three field studies were conducted near Corvallis (44.56, −123.22) and Canby (44.29, −123.23), OR, in 2023 and 2024. At Corvallis, studies were initiated in May (spring) when *C. arvense* plants were 25–35 cm tall (BBCH-19), in a fallow rainfed field on a Willamette silt loam soil (USDA-NRCS, 2023) naturally infested with *C. arvense* and *Daucus carota* L. The Canby study was initiated in June (late-spring) when *C. arvense* was 15–20 cm tall (BBCH-16), in a commercial 5-year-old rainfed hazelnut (*Corylus avellana* cv. 'PollyO') orchard planted at 6.1 by 6.1 m spacing on a Chehalis silty clay loam (USDA-NRCS, 2023). This site was selected because the grower reported poor *C. arvense* control with clopyralid and glyphosate.

Fifteen treatments were evaluated, including mowing alone; florpyrauxifen-benzyl at 29 or 38 g ai ha^{-1}; glyphosate at 1680 g ae ha^{-1}; mesotrione (Callisto; Syngenta Crop Protection, Greensboro, NC) at 210 g ai ha^{-1}; flazasulfuron at 200 g ai ha^{-1}; 2,4-D at 1060 g ae ha^{-1}; glufosinate at 1150 g ai ha^{-1}; and clopyralid at 280 g ai ha^{-1}. Florpyrauxifen-benzyl was applied either as a single spring treatment (A), a single summer treatment (B; 28 days after the spring application), or as sequential applications in spring followed by summer. Two additional treatments consisted of mowing in spring followed by florpyrauxifen-benzyl at 29 or 38 g ai ha^{-1} in summer. Mowing was performed as a single pass using a walk-behind rotary mower (Premier 26; DR Power Equipment, Waukesha, WI, USA) operated at approximately 4.8 km h^{-1}, with a cutting height of approximately 5–8 cm. Sequential treatments were included to evaluate whether one or two applications within a season were required to control successive flushes of *C. arvense* and prevent seed production. A nontreated control was included for comparison. Treatments were arranged in an RCBD with four replications. Plots measured 6 m by 12 m. Herbicide applications were made using a CO_2-pressurized backpack sprayer (R&D Sprayers, Opelousas, LA) calibrated to deliver 187 L ha^{-1} at 275 kPa and 4.8 km h^{-1}. At Corvallis, applications were made with a six-nozzle boom fitted with AIXR-11002 flat-fan nozzles (TeeJet Technologies, Glendale Heights, IL) spaced 50 cm apart. At Canby, applications were made using a three-nozzle boom fitted with AIXR-11002 nozzles, with sprays directed to both sides of the tree row. Average air temperature at application ranged from 16°C to 20°C across sites. Mean air temperature during the 7-days following treatment averaged approximately 16°C in Corvallis and 17°C in Canby. No rainfall occurred within 7 days after treatment at any site or year.

Assessments included weed control and aboveground biomass separated by shoots and inflorescences. Weed control was visually rated on a 0 to 100% scale, where 0% represented no control and 100% represented complete control at 14, 28, 42, 56, and 84 DAIT; however, only data from 84 DAIT are presented for brevity. At 84 DAIT, aboveground biomass was harvested from two randomly placed 0.25-m^2 quadrats per plot, separated into shoots and inflorescences, oven-dried, and weighed.

2.3 | Statistical Analyses

All data were analysed in R software version 4.2.2 (R Core Team 2025). Generalized linear mixed models (GLMMs) were fitted with appropriate error distributions, and fixed effects were tested using analyses of variance at a significance level of $\alpha = 0.05$.

2.3.1 | Greenhouse Studies

Fixed effects included treatment, run, and their interaction, with experimental blocks treated as random effects. Percentage data

TABLE 1 | Control of *Cirsium arvense* with single or sequential applications of florpyrauxifen-benzyl, 56 days after initial treatment in greenhouse studies, data averaged across growth stages.

	Control[a]	
Treatment (g ai ha^{-1})	**%**	
NTC	—	
Florpyrauxifen-benzyl (9)	86	c
Florpyrauxifen-benzyl (18)	87	bc
Florpyrauxifen-benzyl (29)	93	abc
Florpyrauxifen-benzyl (38)	90	abc
Florpyrauxifen-benzyl (9 fb 9)	88	abc
Florpyrauxifen-benzyl (18 fb 18)	94	ab
Florpyrauxifen-benzyl (29 fb 29)	94	a
Florpyrauxifen-benzyl (38 fb 38)	94	a

ANOVA	**Chi-square**	**df**	***p***
Stage	0.016	1	0.90
Treatment	15.14	7	0.03
Stage × Treatment	9.39	7	0.22

Contrast[b]	**Control (%)**	***z*-ratio**	***p***
Single vs. sequential	89 vs. 93	2.071	0.038

Abbreviations: fb, followed by (sequential application; 28 day apart); NTC, nontreated control.
[a]Means within a column followed by the same letter are not significantly different according to Tukey's HSD ($\alpha = 0.05$).
[b]Contrasts were tested using Wald tests; *t*-ratios are reported for models with normal errors, and *z*-ratios for models with beta errors.

TABLE 2 | Root biomass and root biomass reduction of *Cirsium arvense* following single or sequential applications of florpyrauxifen-benzyl, 56 day after initial treatment in greenhouse studies.

	Root weight[a]				Root weight reduction[a]			
	Rosette stage		Bolting stage		Rosette stage		Bolting stage	
Treatment (g ai ha^{-1})	g m^{-2}				%			
NTC	146.17	a	238.62	a		—		—
Florpyrauxifen-benzyl (9)	7.05	b	17.64	b	97	b	80	c
Florpyrauxifen-benzyl (18)	3.68	b	16.06	b	98	ab	91	ab
Florpyrauxifen-benzyl (29)	2.57	b	3.76	b	98	ab	96	a
Florpyrauxifen-benzyl (38)	1.1	b	47.64	b	99	a	93	ab
Florpyrauxifen-benzyl (9 fb 9)	2.17	b	50.22	b	98	ab	86	bc
Florpyrauxifen-benzyl (18 fb 18)	1.87	b	20.62	b	98	ab	89	bc
Florpyrauxifen-benzyl (29 fb 29)	2.73	b	9.78	b	98	ab	95	ab
Florpyrauxifen-benzyl (38 fb 38)	0.85	b	2.98	b	99	a	97	a

ANOVA	Chi-square	df	*p*	ANOVA	Chi-square	df	*p*
Stage	18.56	1	<0.0001	Stage	0.22	1	0.63
Treatment	176.83	8	<0.0001	Treatment	43.94	7	<0.0001
Stage × Treatment	15.94	8	0.04	Stage × Treatment	24.76	7	<0.0001

Contrast[b]	Root weight (g m^{-2})	*t*-ratio	*p*	Contrast[b]	Root weight reduction (%)	*z*-ratio	*p*
Single vs. sequential (Rosette)	3.6 vs. 1.9	−0.199	0.84	Single vs. Sequential (Rosette)	98 vs. 98	0.158	0.87
Single vs. sequential (Bolting)	21.3 vs. 20.9	−0.030	0.97	Single vs. Sequential (Bolting)	90 vs. 92	0.435	0.66

Abbreviations: fb, followed by (sequential application; 28 days apart); NTC, nontreated control.
[a]Means within a column followed by the same letter are not significantly different according to Tukey's HSD ($\alpha = 0.05$).
[b]Contrasts were tested using Wald tests; *t*-ratios are reported for models with normal errors, and *z*-ratios for models with beta errors.

(weed control, shoot biomass reduction, root biomass reduction, and secondary root regrowth) were beta-transformed to a 0–1 scale and analysed with the glmmTMB package (version 1.1.7) using a beta error distribution (Brooks et al. 2017). Data from the nontreated control were excluded since values were zero. Root biomass and the number of secondary shoots regenerated from root segments were analysed separately with GLMMs fitter with a Gaussian distribution, after square-root transformation to satisfy model assumptions. When significant treatment or interaction effects were detected, post hoc comparisons were performed using Tukey's HSD with the emmeans package (version 1.8.5) and the cld function (Lenth 2020).

2.3.2 | Field Studies

Fixed effects included study site, treatment, and their interaction, with blocks as random effects. Percentage data (weed control, shoot biomass reduction, and inflorescence biomass reduction) were beta-transformed as described above and analysed with GLMMs (Brooks et al. 2017). Data from the nontreated control were omitted because values were zero. Significant treatment or interaction effects were followed by Tukey's HSD post hoc comparisons using the emmeans package, as described previously (Lenth 2020).

3 | Results

3.1 | Greenhouse Studies

3.1.1 | Response of *C. arvense* to Florpyrauxifen-Benzyl

Florpyrauxifen-benzyl effectively controlled *C. arvense*, with control ranging from 86% to 94% across rates (9–38 g ha^{-1}) and application timings (single and sequential) (Table 1). Growth stage had a significant effect on control ($p = 0.90$) and no significant stage × treatment interaction ($p = 0.225$) was detected (Table 1). Contrasts indicated that, averaged across growth stages, sequential applications provided significantly greater control than single applications (93% vs. 89%, $p = 0.03$).

Root biomass in the nontreated control averaged 146.2 g at the rosette stage and 238.6 g at the bolting stage (Table 2). All florpyrauxifen-benzyl treatments reduced root biomass by >97% at the rosette stage and by >80% at the bolting stage (Table 2). The greatest reductions were observed at the 38 g ha^{-1} rate, either as a single application (99% rosette) or sequentially (97% bolting). The growth stage significantly affected root biomass ($p < 0.0001$), and there was a notable interaction between the stage and treatment ($p < 0.0001$), indicating reduced efficacy

TABLE 3 | Secondary shoot regrowth and number of secondary shoots in *Cirsium arvense* following single or sequential applications of florpyrauxifen-benzyl, evaluated 56 days after the initial treatment in greenhouse studies.

	Secondary shoot regrowth[a,c]				Secondary shoots[b,c]			
	Rosette stage		Bolting stage		Rosette stage		Bolting stage	
Treatment (g ai ha^{-1})	%				#			
NTC	93	a	82	a	29.33	a	4.8	a
Florpyrauxifen-benzyl (9)	9	b	14	b	1.17	b	2.2	b
Florpyrauxifen-benzyl (18)	6	b	9	b	0.5	b	0.8	c
Florpyrauxifen-benzyl (29)	5	b	6	b	0	b	0	c
Florpyrauxifen-benzyl (38)	5	b	7	b	0	b	0.4	c
Florpyrauxifen-benzyl (9 fb 9)	5	b	7	b	0	b	0.2	c
Florpyrauxifen-benzyl (18 fb 18)	5	b	9	b	0	b	0.4	c
Florpyrauxifen-benzyl (29 fb 29)	5	b	6	b	0	b	0	c
Florpyrauxifen-benzyl (38 fb 38)	5	b	6	b	0	b	0	c

ANOVA	Chi-square	df	*p*	Chi-square	df	*p*
Stage	1.59	1	0.21	170.30	1	< 0.0001
Treatment	110.41	8	< 0.0001	10.53	8	0.23
Stage × Treatment	4.79	8	0.78	155.47	8	< 0.0001

Contrast[d]	Regrowth (%)	*z*-ratio	*p*	Shoots (#)	*t*-ratio	*p*
Single vs. sequential (Rosette)	6 vs. 4	−0.821	0.41	0.41 vs. 0	−0.354	0.72
Single vs. sequential (Bolting)	9 vs. 7	−0.782	0.43	0.85 vs. 0.15	−2.045	0.04

Abbreviations: fb, followed by (sequential application; 28 days apart); NTC, nontreated control.
[a]Secondary shoot regrowth: percentage of root segments that regenerated at least one shoot.
[b]Secondary shoots: number of shoots regenerated.
[c]Means within a column followed by the same letter are not significantly different according to Tukey's HSD ($\alpha = 0.05$).
[d]Contrasts were tested using Wald tests; *t*-ratios are reported for models with normal errors, and *z*-ratios for models with beta errors.

in some treatments at the bolting stage. Contrasts comparisons revealed no significant difference between single and sequential applications for root biomass reduction at either stage ($p > 0.66$), reinforcing the herbicide's high standalone efficacy.

The regeneration of root buds was almost entirely stopped by florpyrauxifen-benzyl (Table 3). In the nontreated control, 93% (rosette) and 82% (bolting) of root segments regenerated within 35 days after transplanting. In contrast, florpyrauxifen-benzyl treated plants had ≤ 14% regeneration, with no significant differences among rates tested or application timings. The number of secondary shoots arising from segments was also significantly reduced; nontreated rosette-stage roots averaged 29.3 shoots, while florpyrauxifen-benzyl treated plants rarely exceeded 2 shoots. At the bolting stage, sequential applications significantly reduced secondary shoot counts more than single applications (0.15 vs. 0.85 shoots, $p = 0.04$), but no differences were detected at the rosette stage ($p = 0.72$).

3.1.2 | Comparison With Other Herbicides

Florpyrauxifen-benzyl at 29 g ha^{-1} provided equivalent *C. arvense* control to glyphosate (1680 g ae ha^{-1}) and clopyralid (280 g ai ha^{-1}), all ≥ 96% control (Table 4; Figure 1). These herbicides significantly outperformed flazasulfuron (200 g ai ha^{-1}), 2,4-D (1,060 g ai ha^{-1}), glufosinate (1680 g ai ha^{-1}), and carfentrazone (35 g ai ha^{-1}). Contrasts indicated no improvement of efficacy when mixing glufosinate or flazasulfuron to florpyrauxifen-benzyl or to clopyralid ($p = 0.89$). Similarly, florpyrauxifen-benzyl or clopyralid containing treatments provided similar control ($p = 0.26$).

Root biomass reduction followed a similar pattern (Table 5; Figure 1), with florpyrauxifen-benzyl (97%), glyphosate (97%), and clopyralid (98%) providing the greatest reductions. Carfentrazone reduced root biomass by only 59%, and 2,4-D by 76%. Secondary shoot regrowth was significantly inhibited by florpyrauxifen-benzyl, glyphosate, and clopyralid (Table 6). Mixtures of florpyrauxifen-benzyl with glufosinate or flazasulfuron did not improve efficacy compared to florpyrauxifen-benzyl alone ($p = 0.06$ for root biomass; $p = 0.47$ for secondary shoots), indicating that under controlled greenhouse conditions, florpyrauxifen-benzyl's performance was maximized as a standalone treatment.

3.2 | Field Study

Efficacy in the field was influenced by site, treatment, and their interaction ($p < 0.0001$; Tables 7–9). At Corvallis.1, single spring applications of florpyrauxifen-benzyl provided 78% to 84% control,

TABLE 4 | Control of *Cirsium arvense* across herbicide and mowing treatments, alone or in combinations, evaluated 56 days after initial treatment in greenhouse studies.

	Rate	Control[a]	
Treatment	**g ai/ae ha^{-1}**	**%**	
NTC	—	—	
Mowing	—	59	b
Florpyrauxifen-benzyl	29	96	a
Glyphosate	1680	98	a
Flazasulfuron	200	76	b
2,4-D	1060	65	b
Clopyralid	280	98	a
Carfentrazone	35	23	c
Glufosinate	1150	68	b
Florpyrauxifen-benzyl + glufosinate	29 + 1150	98	a
Florpyrauxifen-benzyl + flazasulfuron	29 + 200	97	a
Clopyralid + glufosinate	280 + 1150	98	a
Clopyralid + flazasulfuron	280 + 200	98	a
Clopyralid + florpyrauxifen-benzyl	280 + 29	98	a

ANOVA	**Chi-square**	**df**	***p***
Treatment	176.81	12	< 0.0001
Run	0.018	1	0.89
Run × Treatment	11.41	12	0.49

Contrast[b]	**Control (%)**	***z*-ratio**	**p**
Florpyrauxifen-benzyl alone vs. mixtures	96 vs. 98	0.764	0.45
Clopyralid alone vs. mixtures	98 vs. 98	−0.128	0.89
Florpyrauxifen-benzyl vs. clopyralid	97 vs. 98	−0.008	0.26

Abbreviation: NTC, nontreated control.
[a]Means within a column followed by the same letter are not significantly different according to Tukey's HSD ($\alpha = 0.05$).
[b]Contrasts were tested using Wald tests; *t*-ratios are reported for models with normal errors, and *z*-ratios for models with beta errors.

sequential spring followed by summer applications increased control to 82% to 88%, and incorporation of mowing raised it further to 85% to 87% (Table 7). Glyphosate provided 94% and clopyralid 87%, both comparable to the best florpyrauxifen programs, while mesotrione and flazasulfuron were significantly less effective. Shoot biomass reduction followed a similar pattern, with florpyrauxifen-benzyl containing treatments (48%–83%) providing similar reductions as glyphosate and clopyralid (Table 8). Flower biomass reduction was > 92% for sequential or mowing programs, while single summer applications reduced flowers by < 51% (Table 9).

At Corvallis.2, overall performance was slightly lower and more variable (Table 7). Single spring applications of florpyrauxifen-benzyl provided 78% to 80% control, with sequential and mowing programs providing statistically similar control, 69% to 87%. Single summer applications of florpyrauxifen-benzyl were less effective, providing < 35% control. Shoot biomass reduction ranged from 41% to 59% for single applications to 87% to 94% for mowing followed by florpyrauxifen (Table 8). Flower biomass reduction again was greatest with sequential or mowing programs, at 84% to 87%, and lowest for single summer application, 13% to 70% (Table 9).

At Canby, where *C. arvense* has survived clopyralid in previous years, overall control was reduced (Table 7). Single spring applications of florpyrauxifen-benzyl provided 36% to 48% control, while sequential and mowing programs increased control to 54% to 73%. Glyphosate and clopyralid provided similar control to sequential or mowing florpyrauxifen-benzyl programs. Shoot biomass reductions were lower overall, ranging from 12% to 68% for single applications of florpyrauxifen-benzyl, but mowing followed by florpyrauxifen improved reductions to 65% to 88% (Table 8). Flower biomass reduction was statistically similar across treatments, > 91% (Table 9).

Contrasts across sites confirmed the significance of these differences (Tables 7–9). Single spring applications outperformed summer applications, 69% versus 30% control ($p < 0.0001$). Sequential applications improved control compared to single applications, 77% versus 49% ($p < 0.0001$). Mowing followed by florpyrauxifen also significantly increased control compared to single applications, 79% versus 49% ($p < 0.0001$). However, sequential applications and mowing plus florpyrauxifen-benzyl were not significantly different, 77% versus 79% ($p = 0.56$). When single and sequential treatments were pooled, they were less effective than mowing programs, 58% versus 79% ($p < 0.0001$). For shoot biomass reduction (Table 8), mowing followed by florpyrauxifen-benzyl significantly improved biomass reduction compared to single applications (47% vs. 74%, $p = 0.0001$), while sequential applications did not improve biomass reduction compared to single applications (51% vs. 47%, $p = 0.61$). Flower biomass contrasts showed the same patterns (Table 9). Spring applications of florpyrauxifen-benzyl significantly outperformed summer applications, 89% vs. 56% ($p < 0.0001$), while sequential and mowing programs provided comparable flower reduction, both 91%, and significantly greater than single applications, which averaged 72% (sequential vs. single: $p < 0.0001$; mowing vs. single: $p = 0.002$).

4 | Discussion

This study provides the first comprehensive evaluation of florpyrauxifen-benzyl on *C. arvense*. Across greenhouse and field settings, florpyrauxifen-benzyl effectively controlled *C. arvense*, reduced root biomass, and limited root bud regeneration to levels comparable with glyphosate and clopyralid (Figure 1), the benchmarks for perennial broadleaf weed control. These outcomes are especially significant for *C. arvense*, as its persistence is influenced by clonal propagation from its extensive root system (Donald 1993; Tiley 2010).



FIGURE 1 | Root biomass of *Cirsium arvense* following different herbicide treatments compared to a nontreated control in greenhouse studies. Treatments included clipping (mowing), florpyrauxifen 29 g ai ha^{-1}, 2,4-D 1060 g ai ha^{-1}, clopyralid 280 g ai ha^{-1}, glyphosate 1680 g ae ha^{-1}, flazasulfuron 200 g ha^{-1}, carfentrazone 35 g ai ha^{-1}, and glufosinate 1150 g ai ha^{-1}. Visible reductions in root mass illustrate the differential efficacy of systemic versus contact herbicides, with florpyrauxifen-benzyl showing efficacy comparable to benchmark standards glyphosate and clopyralid.

TABLE 5 | Root biomass and root biomass reduction of *Cirsium arvense* across herbicide and mowing treatments, 56 days after initial treatment in greenhouse studies.

	Rate	Root weight[a]		Root weight reduction[a]	
Treatment	**g ai/ae ha^{-1}**	**g**		**%**	
NTC	—	120.4	a	—	
Mowing	—	28.4	cd	76	cd
Florpyrauxifen-benzyl	29	1.9	e	97	a
Glyphosate	1680	3.1	e	97	a
Flazasulfuron	200	40.2	bc	71	de
2,4-D	1060	30.3	bcd	76	cd
Clopyralid	280	1.1	e	98	a
Carfentrazone	35	49.8	b	59	e
Glufosinate	1150	17.2	de	85	bc
Florpyrauxifen-benzyl + glufosinate	29 + 1150	12.4	de	89	bc
Florpyrauxifen-benzyl + flazasulfuron	29 + 200	12.1	de	90	ab
Clopyralid + glufosinate	280 + 1150	3.8	e	96	a
Clopyralid + flazasulfuron	280 + 200	1.0	e	98	a
Clopyralid + florpyrauxifen-benzyl	280 + 29	1.2	e	98	a

ANOVA	**Chi-square**	**df**	***p***	**Chi-square**	**df**	***p***
Treatment	255.85	13	< 0.0001	168.02	12	< 0.0001
Run	0.01	1	0.97	0.06	1	0.98
Run × Treatment	2.93	13	0.99	1.52	12	0.99

Contrast[b]	**Root weight (g)**	***t*-ratio**	***p***	**Root weight reduction (%)**	***z*-ratio**	***p***
Florpyrauxifen-benzyl alone vs. mixtures	2 vs. 7	1.259	0.21	97 vs. 94	−3.274	0.06
Clopyralid alone vs. mixtures	1 vs. 2	0.110	0.91	98 vs. 97	−0.454	0.65
Florpyrauxifen-benzyl vs. clopyralid	6 vs. 2	0.735	0.46	94 vs. 97	−2.165	0.03

Abbreviation: NTC, nontreated control.
[a]Means within a column followed by the same letter are not significantly different according to Tukey's HSD ($\alpha = 0.05$).
[b]Contrasts were tested using Wald tests; *t*-ratios are reported for models with normal errors, and *z*-ratios for models with beta errors.

TABLE 6 | Shoot regrowth of *Cirsium arvense* following herbicide or mowing treatments, evaluated 56 days after initial treatment in greenhouse studies.

Treatment	Rate	Shoots regrowth[a]	
	g ai/ae ha^{-1}	#	
NTC	—	7.6	a
Mowing	—	2	cd
Florpyrauxifen-benzyl	29	0	d
Glyphosate	1680	0	d
Flazasulfuron	200	2.4	bcd
2,4-D	1060	2.2	cd
Clopyralid	280	0	d
Carfentrazone	35	5.2	ab
Glufosinate	1150	3.2	bc
Florpyrauxifen-benzyl + glufosinate	29 + 1150	0.4	cd
Florpyrauxifen-benzyl + flazasulfuron	29 + 200	1.4	cd
Clopyralid + glufosinate	280 + 1150	0.4	cd
Clopyralid + flazasulfuron	280 + 200	0	d
Clopyralid + florpyrauxifen-benzyl	280 + 29	0	d

ANOVA	Chi-square	df	*p*
Treatment	65.77	13	< 0.0001
Run	0.03	1	0.85
Run × Treatment	16.45	13	0.23

Contrast[b]	Shoots (#)	*t*-ratio	*p*
Florpyrauxifen-benzyl alone vs. mixtures	0.1 vs. 0.7	0.723	0.47
Clopyralid alone vs. mixtures	0 vs. 0.1	0.114	0.91
Florpyrauxifen-benzyl vs. clopyralid	0.4 vs. 0.1	0.402	0.69

Abbreviation: NTC, nontreated control.
[a]Means within a column followed by the same letter are not significantly different according to Tukey's HSD ($\alpha = 0.05$).
[b]Contrasts were tested using Wald tests; *t*-ratios are reported for models with normal errors, and *z*-ratios for models with beta errors.

Reproductive suppression is another critical outcome of this study. Florpyrauxifen-benzyl, when applied sequentially or after mowing, reduced flower biomass by up to 90%, compared to only 56% from single summer applications. Limiting flower production is critical because *C. arvense* produces large numbers of wind-dispersed seeds that readily colonize new areas (Becker et al. 2008). Long-term management strategies are most effective when they deplete root reserves and prevent seed input simultaneously (Davis et al. 2018; Orloff et al. 2018).

In the greenhouse, florpyrauxifen-benzyl reduced root biomass by ≥ 97% at the rosette stage and ≥ 80% at the bolting stage, and limited bud regeneration to ≤ 14% of segments. These reductions indicate effective systemic movement to root tissues. Clopyralid is regarded as the most effective auxin on *C. arvense* because of its systemic activity and root suppression (Baccin and Moretti 2024). The present results indicate that florpyrauxifen-benzyl may achieve a comparable level of efficacy, particularly at the rosette stage, when carbohydrate reserves are low and sinks are active (McAllister and Haderlie 1985b; Nkurunziza and Streibig 2011).

When treatments with comparable cumulative doses were considered in the greenhouse study, sequential applications provided similar efficacy to single higher-rate applications. For example, the sequential 9 g ha^{-1} followed by 9 g ha^{-1} treatment provided control comparable to the single 18 g ha^{-1} application, with control values ranging from approximately 90% to 92% depending on growth stage. Likewise, the sequential 18 g ha^{-1} program resulted in control similar to the single 38 g ha^{-1} application, with both treatments providing ≥ 92% control and not differing statistically. These results suggest that distributing the herbicide dose across two applications did not substantially alter overall efficacy under greenhouse conditions.

While sequential applications of florpyrauxifen-benzyl offered little benefit in the greenhouse, they were beneficial in the field. Contrasts confirmed that sequential applications provided significantly greater control than single applications (77% vs. 49%, $p < 0.0001$). This outcome was expected, as sequential applications increased cumulative herbicide exposure and allowed treatment of regrowth and late-emerging shoots not present or fully exposed during the initial application. In field populations of *C. arvense*, plants often occur at multiple growth stages and new flushes may emerge following initial injury or removal of aboveground tissues. Thus, the benefits of sequential applications likely reflect plant size heterogeneity, regrowth dynamics, competitive interactions, and environmental conditions that can constrain the performance of a single application (Tavaziva et al. 2019). This is consistent with earlier findings where auxinic herbicides provide inconsistent reductions in *C. arvense* roots, largely because uptake and movement to belowground sinks varies with growth stage and environmental conditions (Tavaziva et al. 2019). Florpyrauxifen-benzyl also proved effective when integrated with mowing, particularly in reducing shoot and flower biomass of *C. arvense*. Previous research has shown that mowing or tillage alone often exacerbate *C. arvense* infestations by stimulating bud development (Larson et al. 2024), but when combined with auxin herbicides, mowing can improve uptake and translocation to underground tissues (Beck and Sebastian 2000; Enloe et al. 2007). In the present study, mowing likely removed mature shoots and stimulated new regrowth that was younger and physiologically more susceptible to herbicide activity. These regrowing shoots likely had lower carbohydrate reserves and stronger sink activity, which may have enhanced herbicide uptake and movement to underground tissues (Bicksler and Masiunas 2009; Tavaziva et al. 2019). This approach is particularly relevant in perennial cropping systems such as orchards and vineyards, where a mid-season mowing-herbicide program can be operationally feasible

TABLE 7 | Control of *Cirsium arvense* 84 days after the initial treatment in field experiments at Corvallis and Canby, OR.

Treatment	Rate g ai/ae ha^{-1}	Application timing[a]	Corvallis.1[b]		Corvallis.2[b]		Canby[b]	
			%					
NTC	—	—	—		—		—	
Mowing	—	A	17	ef	5	f	4	f
Florpyrauxifen-benzyl	29	A	84	ab	80	ab	48	bcde
Florpyrauxifen-benzyl	38	A	78	b	78	ab	36	de
Glyphosate	1680	A	94	a	91	a	68	ab
Mesotrione	210	A	45	cd	7.4	ef	28	e
Flazasulfuron	200	A	13	f	41	cd	64	abc
2,4-D	1060	A	80	b	81	ab	45	bcde
Glufosinate	1150	A	55	c	37	d	38	cde
Clopyralid	280	A	87	ab	84	ab	68	ab
Florpyrauxifen-benzyl	29	A fb B	82	b	80	ab	73	a
Florpyrauxifen-benzyl	38	A fb B	88	ab	69	bc	64	abc
Florpyrauxifen-benzyl	29	B	34	de	21	de	3	f
Florpyrauxifen-benzyl	38	B	47	cd	35	d	54	abcd
Mowing fb florpyrauxifen-benzyl	– + 29	A fb B	85	ab	84	ab	59	abcd
Mowing fb florpyrauxifen-benzyl	– + 38	A fb B	87	ab	85	ab	65	abc

ANOVA	Chi-square	df	*p*
Site	9.12	2	0.001
Treatment	198.18	14	< 0.0001
Site × Treatment	95.40	28	< 0.0001

Contrast[c]	Control (%)	*z*-ratio	*p*
Single spring vs. single summer	69 vs. 30	−5.772	< 0.0001
Single vs. sequential applications	49 vs. 77	5.272	< 0.0001
Single vs. incorporation of mowing	49 vs. 79	5.435	< 0.0001
Sequential vs. incorporation of mowing	77 vs. 79	0.574	0.56
Single + sequential vs. incorporation of mowing	58 vs. 79	4.520	< 0.0001

Abbreviations: –, not applicable; fb, followed by (sequential application; 28 days apart); NTC, nontreated control.
[a]Application timing: A = spring application; B = summer application, applied 28 days after A.
[b]Means within a column followed by the same letter are not significantly different according to Tukey's HSD ($\alpha = 0.05$).
[c]Contrasts were tested using Wald tests; *t*-ratios are reported for models with normal errors, and *z*-ratios for models with beta errors.

integrated. Florpyrauxifen-benzyl is currently registered for use in several cropping systems, including rice and selected perennial crop environments. These registrations indicate its utility in production systems where broadleaf weed management is important, and the level of suppression of *C. arvense* observed here suggests it could contribute to integrated management programs in these crops.

No weed control improvement was observed from mixing florpyrauxifen-benzyl with glufosinate or flazasulfuron under greenhouse conditions. Similar results have been reported for other auxin programs, where mixtures rarely enhance suppression of *C. arvense* itself (Davis et al. 2018). Importantly, mixing flazasulfuron or glufosinate did not reduce florpyrauxifen-benzyl efficacy. In the field, such mixtures may still be valuable in the field to broaden the spectrum, especially in fields with mixed infestations (Miranda and Moretti 2025).

Although studies of florpyrauxifen-benzyl on *C. arvense* have not been reported, research on other perennials supports its efficacy. In rice systems, for instance, florpyrauxifen-benzyl reduced tuber sprouting and regrowth of *Cyperus rotundus* (Miller and Norsworthy 2018b). Its strong efficacy on perennial tissues in those studies aligns with the root suppression observed here

TABLE 8 | Shoot biomass reduction of *Cirsium arvense* 84 days after the initial treatment in field experiments at Corvallis and Canby, OR.

Treatment	Rate g ai/ae ha^{-1}	Application timing[a]	Corvallis.1[b]		Corvallis.2[b]		Canby[b]	
			%					
NTC	—	—	—		—		—	
Mowing	—	A	58	abcd	74	abc	59	b
Florpyrauxifen-benzyl	29	A	53	abcd	41	abc	68	ab
Florpyrauxifen-benzyl	38	A	48	bcd	51	abc	56	b
Glyphosate	1680	A	44	bcd	82	abc	89	a
Mesotrione	210	A	20	d	79	abc	52	b
Flazasulfuron	200	A	67	abc	20	c	75	ab
2,4-D	1060	A	67	abc	68	bc	65	ab
Glufosinate	1150	A	57	abcd	40	abc	16	c
Clopyralid	280	A	23	cd	78	abc	75	ab
Florpyrauxifen-benzyl	29	A fb B	58	abcd	58	abc	66	ab
Florpyrauxifen-benzyl	38	A fb B	50	abcd	32	bc	74	ab
Florpyrauxifen-benzyl	29	B	46	abcd	24	c	12	c
Florpyrauxifen-benzyl	38	B	83	a	59	abc	50	b
Mowing fb florpyrauxifen-benzyl	– + 29	A fb B	68	ab	87	ab	65	ab
Mowing fb florpyrauxifen-benzyl	– + 38	A fb B	56	abcd	94	a	88	a

ANOVA	Chi-square	df	*p*
Site	0.191	2	0.91
Treatment	34.472	14	0.001
Site × Treatment	71.705	28	< 0.0001

Contrast[c]	Biomass reduction (%)	*z*-ratio	*p*
Single spring vs. single summer	50 vs. 43	0.693	0.48
Single vs. sequential applications	47 vs. 51	0.506	0.61
Single vs. incorporation of mowing	47 vs. 74	3.823	0.0001
Sequential vs. incorporation of mowing	51 vs. 74	2.941	0.003
Single + sequential vs. incorporation of mowing	48 vs. 74	4.381	< 0.0001

Abbreviations: –, not applicable; fb, followed by (sequential application; 28 days apart); NTC, nontreated control.
[a]Application timing: A = spring application; B = summer application, applied 28 days after A.
[b]Means within a column followed by the same letter are not significantly different according to Tukey's HSD ($\alpha = 0.05$).
[c]Contrasts were tested using Wald tests; *t*-ratios are reported for models with normal errors, and *z*-ratios for models with beta errors.

in *C. arvense*. These results reinforce its potential as a systemic herbicide for perennial weed management beyond annual species where its use is currently most documented. From a practical standpoint, the results of the field experiments indicate that florpyrauxifen-benzyl could be incorporated into management programs targeting regrowth flushes of *C. arvense*. For example, sequential applications may improve control by targeting shoots that emerge after the initial treatment, while programs integrating mowing followed by herbicide application may enhance suppression by stimulating regrowth that is more susceptible to herbicide activity. These approaches may be particularly relevant in perennial cropping systems, where mowing and herbicide applications are already commonly used as part of orchard floor management.

5 | Conclusion

Florpyrauxifen-benzyl is an effective tool for *C. arvense* management, matching or exceeding the performance of current standards such as glyphosate and clopyralid in terms of shoot biomass reduction, root biomass reduction, and inhibition of root bud regeneration. Under controlled greenhouse conditions, single applications achieved ≥ 86% control and ≥ 97% root biomass reduction. Field performance was optimized with sequential applications or combination with mowing, particularly when treatments targeted actively growing spring-season shoots. Given its distinct receptor preference within the auxin (TIR1/AFB) pathway, florpyrauxifen-benzyl offers

TABLE 9 | Flower biomass reduction of *Cirsium arvense* 84 days after the initial treatment in field experiments at Corvallis and Canby, OR.

Treatment	Rate g ai/ae ha^{-1}	Application timing[a]	Corvallis.1[b]		Corvallis.2[b]		Canby[b]
			%				
NTC	—	—	—		—		—
Mowing	—	A	20	c	34	bc	91
Florpyrauxifen-benzyl	29	A	92	ab	87	a	97
Florpyrauxifen-benzyl	38	A	94	a	80	ab	95
Glyphosate	1680	A	92	ab	84	a	97
Mesotrione	210	A	42	bc	70	ab	95
Flazasulfuron	200	A	66	abc	80	ab	97
2,4-D	1060	A	94	ab	83	a	97
Glufosinate	1150	A	86	ab	69	ab	97
Clopyralid	280	A	94	a	84	a	97
Florpyrauxifen-benzyl	29	A fb B	96	a	87	a	98
Florpyrauxifen-benzyl	38	A fb B	92	ab	84	a	98
Florpyrauxifen-benzyl	29	B	51	abc	13	c	97
Florpyrauxifen-benzyl	38	B	13	c	70	ab	95
Mowing fb florpyrauxifen-benzyl	− + 29	A fb B	94	a	87	a	96
Mowing fb florpyrauxifen-benzyl	− + 38	A fb B	94	a	84	a	97

ANOVA	Chi-square	df	*p*
Site	12.708	2	0.001
Treatment	50.089	14	< 0.0001
Site × Treatment	42.315	28	0.04

Contrast[c]	Biomass reduction (%)	*z*-ratio	*p*
Single spring vs. single summer	89 vs. 56	−4.881	< 0.0001
Single vs. sequential applications	72 vs. 91	3.958	< 0.0001
Single vs. incorporation of mowing	72 vs. 91	3.701	0.002
Sequential vs. incorporation of mowing	91 vs. 91	−0.120	0.90
Single + sequential vs. incorporation of mowing	78 vs. 91	2.632	0.008

Abbreviations: —, not applicable; fb, followed by (sequential application; 28 days apart); NTC, nontreated control.
[a]Application timing: A = spring application; B = summer application, applied 28 days after A.
[b]Means within a column followed by the same letter are not significantly different according to Tukey's HSD ($\alpha = 0.05$).
[c]Contrasts were tested using Wald tests; *t*-ratios are reported for models with normal errors, and *z*-ratios for models with beta errors.

opportunities to diversify herbicide programs, reduce dependence on glyphosate and clopyralid, and mitigate the risk of resistance evolution. Adoption of this herbicide should be within an integrated management strategy that includes cultural, mechanical, and other non-chemical strategies to manage *C. arvense* and maintain the sustainability of perennial cropping systems.

Acknowledgements

The authors gratefully acknowledge the financial support received from the Oregon Hazelnut Commission, the Inter-Regional Program 4 (IR-4), and the Ferrero Hazelnut Company to conduct this project. They also sincerely thank the growers who graciously provided space within their orchards to conduct this research.

Funding

This work was supported by the Oregon Hazelnut Commission; USDA-IR4; Ferrero Hazelnut Company.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Peer Review

For transparency, the peer review documents associated with this article are available at https://doi.org/10.1111/wre.70090.

References

Baccin, L., and M. L. Moretti. 2024. "Clopyralid Applied With Sponge Wiper for *Cirsium arvense* Control in Hops in the Western United States." *Crop Protection* 177: 106518.

Beck, K. G., and J. R. Sebastian. 2000. "Combining Mowing and Fall-Applied Herbicides to Control Canada Thistle (*Cirsium arvense*)." *Weed Technology* 14: 351–356.

Becker, R., M. Haar, B. Kincaid, L. Klossner, and F. Forcella. 2008. "Production and Wind Dispersal of Canada Thistle (*Cirsium arvense* L.) Achenes." Minnesota Department of Transportation.

Bicksler, A. J., and J. B. Masiunas. 2009. "Canada Thistle (*Cirsium arvense*) Suppression With Buckwheat or Sudangrass Cover Crops and Mowing." *Weed Technology* 23: 556–563.

Bourdôt, G. W., B. Basse, and M. G. Cripps. 2016. "Mowing Strategies for Controlling *Cirsium arvense* in a Permanent Pasture in New Zealand Compared Using a Matrix Model." *Ecology and Evolution* 6: 2968–2977.

Brooks, M. E., K. Kristensen, K. J. van Benthem, et al. 2017. "glmmTMB Balances Speed and Flexibility Among Packages for Zero-Infsummerd Generalized Linear Mixed Modeling." *R Journal* 9: 378–400.

Carlson, S. J., and W. W. Donald. 1988. "Glyphosate Effects on Canada Thistle (*Cirsium arvense*) Roots, Root Buds, and Shoots." *Weed Research* 28: 37–45.

Davis, S., J. Mangold, F. Menalled, N. Orloff, Z. Miller, and E. Lehnhoff. 2018. "A Meta-Analysis of Canada Thistle (*Cirsium arvense*) Management." *Weed Science* 66: 548–557.

Donald, W. W. 1984. "Chlorsulfuron Effects on Shoot Growth and Root Buds of Canada Thistle (*Cirsium arvense*)." *Weed Science* 32: 42–50.

Donald, W. W. 1992. "Fall-Applied Herbicides for Canada Thistle (*Cirsium arvense*) Root and Root Bud Control in Reduced-Till Spring Wheat." *Weed Technology* 6: 252–261.

Donald, W. W. 1993. "Root Versus Shoot Measurements to Evaluate Recovery of Canada Thistle (*Cirsium arvense*) After Several Years of Control Treatments." *Canadian Journal of Plant Science* 73: 369–373.

Enloe, S. F., R. G. Lym, R. Wilson, et al. 2007. "Canada Thistle (*Cirsium arvense*) Control With Aminopyralid in Range, Pasture, and Noncrop Areas." *Weed Technology* 21: 890–894.

Foote, L. E., D. L. Kill, and C. S. Williams. 1970. "Canada Thistle Control on Roadsides." *Weed Science* 18: 307–310.

Hodgson, J. M. 1970. "The Response of Canada Thistle Ecotypes to 2,4-D, Amitrole, and Intensive Cultivation." *Weed Science* 18: 253–255.

Hunter, J. H. 1996. "Control of Canada Thistle (*Cirsium arvense*) With Glyphosate Applied at the Bud vs. Rosette Stage." *Weed Science* 44: 934–938.

Larson, C. D., K. Hettinger, P. M. Carr, et al. 2024. "Tillage and Crop Sequences for Organic *Cirsium arvense* Management in the Northern Great Plains." *Agronomy Journal* 116: 2701–2714.

Lenth, R. 2020. "emmeans: Estimated Marginal Means, Aka Least-Squares Means." R Package Version 1.5.1. https://CRAN.R-project.org/package=emmeans.

McAllister, R. S., and L. C. Haderlie. 1985a. "Effects of Photoperiod and Temperature on Root Bud Development and Assimisummer Translocation in Canada Thistle (*Cirsium arvense*)." *Weed Science* 33: 148–152.

McAllister, R. S., and L. C. Haderlie. 1985b. "Seasonal Variations in Canada Thistle (*Cirsium arvense*) Root Bud Growth and Root Carbohydrate Reserves." *Weed Science* 33: 44–49.

Miller, B. R., and R. G. Lym. 1998. "Using the Rosette Technique for Canada Thistle (*Cirsium arvense*) Control in Row Crops." *Weed Technology* 12: 699–706.

Miller, M. R., and J. K. Norsworthy. 2018a. "Row Crop Sensitivity to Low Rates of Foliar-Applied Florpyrauxifen-Benzyl." *Weed Technology* 32: 398–403.

Miller, M. R., and J. K. Norsworthy. 2018b. "Florpyrauxifen-Benzyl Weed Control Spectrum and Tank-Mix Compatibility With Other Commonly Applied Herbicides in Rice." *Weed Technology* 32: 319–325.

Miranda, J. W. A., and M. L. Moretti. 2025. "Limited Efficacy of Florpyrauxifen-Benzyl Alone for *Lolium perenne* L. spp. *Multiflorum* and *Poa annua* L. Control: The Need for Herbicide Combinations in Hazelnut (*Corylus avellana* L.) Orchard Management." *Weed Research* 65: e70001.

Mitich, L. W. 1988. "Thistles I: *Cirsium* and *Carduus*." *Weed Technology* 2: 228–229.

Morishita, D. W. 1999. "Biology and Management of Noxious Rangeland Weeds: Canada Thistle." In *Biology and Management of Noxious Rangeland Weeds*, edited by R. L. Sheley and J. K. Petroff. Oregon State University Press.

Nkurunziza, L., and J. C. Streibig. 2011. "Carbohydrate Dynamics in Roots and Rhizomes of *Cirsium arvense* and *Tussilago farfara*." *Weed Research* 51: 461–468.

Orloff, N., J. Mangold, Z. Miller, and F. Menalled. 2018. "A Meta-Analysis of Field Bindweed (*Convolvulus arvensis* L.) and Canada Thistle (*Cirsium arvense* L.) Management in Organic Agricultural Systems." *Agriculture, Ecosystems & Environment* 254: 264–272.

Peterson, M. A., A. Collavo, R. Ovejero, V. Shivrain, and M. J. Walsh. 2018. "The Challenge of Herbicide Resistance Around the World: A Current Summary." *Pest Management Science* 74: 2246–2259.

Prusinska, J., V. Uzunova, P. Schmitzer, M. Weimer, J. Bell, and R. M. Napier. 2023. "The Differential Binding and Biological Efficacy of Auxin Herbicides." *Pest Management Science* 79: 1305–1315.

R Core Team. 2025. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing.

Sciegienka, J., E. Keren, and F. Menalled. 2011. "Impact of Root Fragment Dimension, Weight, Burial Depth, and Water Regime on *Cirsium arvense* Emergence and Growth." *Canadian Journal of Plant Science* 91: 1027–1036.

Tavaziva, V. J., T. Verwijst, and A. Lundkvist. 2019. "Growth and Development of *Cirsium arvense* in Relation to Herbicide Dose, Timing of Herbicide Application, and Crop Presence." *Acta Agriculturae Scandinavica Section B Soil and Plant Science* 69: 189–198.

Tiley, G. E. D. 2010. "Biological Flora of the British Isles: *Cirsium arvense* (L.) Scop." *Journal of Ecology* 98: 938–983.

Wang, H., X. Sun, J. Yu, J. Li, and L. Dong. 2021. "The Phytotoxicity Mechanism of Florpyrauxifen-Benzyl to *Echinochloa crus-galli* (L.) P. Beauv. and Weed Control Effect." *Pesticide Biochemistry and Physiology* 179: 104978.

Ziska, L. H., S. Faulkner, and J. Lydon. 2004. "Changes in Biomass and Root:Shoot Ratio of Field-Grown Canada Thistle (*Cirsium arvense*), a Noxious Invasive Weed, With Elevated CO_2: Implications for Control With Glyphosate." *Weed Science* 52: 584–588.