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Tillage and crop sequences for organic *Cirsium arvense* management in the Northern Great Plains

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Abstract

The perennial rhizomatous weed *Cirsium arvense* (L.) Scop. is difficult to manage on semiarid organic farms. Our objective was to quantify the impact of eight 4-year crop sequences crossed with standard- and reduced-tillage on *C. arvense* occurrence (presence/absence), stem density, and aboveground biomass at two semiarid sites in Montana. The sequences represented a range of crop competition from high (multiple years of perennial forage [alfalfa, *Medicago sativa* L.]) to low (2 years of continuous fallow), with intermediate sequences consisting of different annual species. Final-year spring wheat (*Triticum aestivum* L. emend. Thell.) was planted in all sequences to determine impacts on subsequent cash crop production. Through time, alfalfa and double fallow sequences reduced *C. arvense* density and biomass where it was established, although its invasion into new areas increased in the double fallow. Final-year *C. arvense* occurrence and stem density were lower in the alfalfa sequence compared with six and four annual crop sequences, respectively ($p < 0.05$). Final year *C. arvense* biomass was higher at one site than the other, although not in the double fallow sequence. Wheat grain yields differed in response to crop sequences at the two sites: at one site, grain yield was lowest in the alfalfa sequence, especially when standard-tillage was used, while yields were highest in the alfalfa and double fallow sequences at the other site. Using perennial forages in semiarid organic systems can be effective for managing *C. arvense*, but subsequent cash crop yield may be depressed.

1 | INTRODUCTION

Across the Northern Great Plains (NGP) of the United States, *Cirsium arvense* (Canada or creeping thistle) is a weed of particular concern to organic producers (Organic Advisory and Education Council, 2013). As a rhizomatous perennial forb, *C. arvense* can produce an abundance of airborne seeds easily transported great distances or spread readily through vegetative propagation. Seedbed preparation and weed management can create, move, and bury small root fragments of *C. arvense*, which then form adventitious roots and further the infestation (Gustavsson, 1997; Sciegienka et al., 2011; Stolcova, 2002). This capacity, coupled with high airborne seed production, makes this species exceptionally challenging to control in organic agriculture.

Abbreviations: CARC, Central Agricultural Research Center; FE, Fort Ellis Research Farm; NGP, Northern Great Plains.

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In the NGP and similar semiarid regions, many organic producers rely on repeated mechanical cultivation for suppression of *C. arvense* and other perennial rhizomatous weeds (Hettinger et al., 2023; McErlich & Boydston, 2014). Within tilled systems, *C. arvense* populations decline in response to increasing amounts of soil cultivation (Tiley, 2010). However, soil erosion and water loss due to intensive cultivation make the option untenable for long-term management of *C. arvense* in dryland cropping regions like the NGP (Carr et al., 2012; Tanaka et al., 2007).

Reduced- and no-tillage systems often have soils with greater soil aggregate stability and faster infiltration rates with less erosion when compared to standard-tillage systems (Hettinger et al., 2023). However, the use of reduced-tillage methods generally results in higher weed biomass with a higher prevalence of perennial weeds in organic systems (Larson et al., 2021). In organic no-tillage systems, Carr et al. (2013) concluded that established perennial weeds were not suppressed by cover crop mulch. Surveys of organic grain producers in the NGP have also reiterated that no-tillage systems are not widely used (Organic Advisory and Education Council, 2013; Tautges et al., 2016). Integrating livestock grazing into cropping systems can control weeds (Hilimire, 2011) and, in the NGP, has been proposed as an alternative to tillage for cover crop termination and weed control (Kumar et al., 2019; Larson et al., 2024). However, studies on crop–livestock integration in the region have provided mixed results in suppressing weeds (Barroso et al., 2015; Larson et al., 2021, 2024).

Cultural weed management using competitive crops and crop sequences is often coupled with mechanical practices in organic agriculture (Liebman et al., 1997). Annual crops vary in their ability to compete with the deeper rooted *C. arvense*. Cereal crops compete better with perennial weeds than broadleaf annuals (Ghimire et al., 2018; Lenssen et al., 2015). Deep-rooted biennials (e.g., sweet clover [*Melilotus officinalis* L.]) and perennial broadleaf forages (e.g., alfalfa [*Medicago sativa*] and perennial grassland pastures) are better competitors with *C. arvense* than annual crop species (Gramig et al., 2024; Melander et al., 2016). While successful in suppressing perennial weeds like *C. arvense*, deep-rooted forage/cover crops can deplete soil water levels and depress subsequent grain yields in dryland agricultural systems (Miller et al., 2019, 2023). Thus, it is crucial to understand the potential trade-offs of contrasting weed management strategies in dryland organic agricultural productions.

Our objective was to identify effective crop sequences and tillage regimes for suppressing *C. arvense* in semiarid organic wheat (*Triticum aestivum*) production, and determine their effect on subsequent cash crop production. At two Montana sites, *C. arvense* populations were compared among eight 4-year crop sequences that differed in degree of crop competition and tillage intensity during the first 3 years of the study, with final-year wheat production in all sequences. Our hypotheses were as follows: (1) Crop sequences that use a perennial forage crop or consecutive years of intensively managed fallow would provide better *C. arvense* suppression than sequences featuring consecutive years of annual crops; (2) Standard-tillage would suppress *C. arvense* more effectively than reduced-tillage practices; (3) Final-year wheat grain yield would be inversely related to crop sequence competition, especially when standard-tillage practices were used, lowest in the perennial forage crop sequence, and highest when the sequence included consecutive years of fallow.

Core Ideas

- Consecutive years of alfalfa or tilled fallow reduced *Cirsium arvense*.
- Wheat yield was elevated following consecutive years of fallow.
- Alfalfa-induced wheat yield depression occurred at the site where severe drought persisted.
- Reduced-tillage practices provided the same *Cirsium arvense* control as standard-tillage practices.

2 | METHODS

2.1 | Site description

Field experiments were conducted at two Montana State University research locations: Central Agricultural Research Center (CARC; 47°03′33.8′ N lat., 109°56′53.5′ W long., 1400 m elevation) and Fort Ellis Research Farm (FE; 45°40′02.9′ N lat., 110°58′40.4′ W long., 1500 m elevation). The Köppen climate classification (Kottek et al., 2006) for the research center locations is cold semiarid (BSk), with cold winters and warm to hot summers (Padbury et al., 2002). Winter precipitation occurs primarily as snow, while precipitation is erratic in the summer with extended dry periods being common. Both sites have a mean annual temperature of 6.5°C; FE receives an average of 511 mm of precipitation annually, whereas the CARC receives an average of 401 mm of precipitation (1993–2022; PRISM Climate Group, 2023). Precipitation and temperature study site data for the duration of the experiment can be found in Table S1. The soil at FE is a Blackmore silt loam (fine-silty, mixed, superactive, frigid Typic Argiustoll), and the soil at CARC is a Danvers–Judith clay loam (fine, smectitic, frigid Vertic Argiustolls and fine-loamy, carbonatic, frigid Typic Calciustoll; Soil Survey Staff, 2023).

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2.2 | Experimental design

At each site, 4-year crop sequences were established, although the duration of the field experiments was offset by a year between the sites: CARC (2019–2022) and FE (2020–2023). Eight crop sequences were crossed with two tillage systems over the 4 years. At CARC, in a field that was summer fallowed the year prior to the study, treatments were arranged in a randomized complete block design, with four blocks and 16 plots (6.0 m × 9.1 m) in each block. Treatment (crop sequence × tillage) was assigned to the plot level, with each treatment replicated in each block (Figure S1). Plots within block were separated by a 3-m buffer, with 15-m-wide alleys between each block.

At FE, in a field that was planted to spring wheat the year prior to the study, the experiment was conducted in six blocks (15 m × 90 m) located in existing patches of *C. arvense*, with a minimum distance between blocks of 3 m and a maximum distance of 250 m. Tillage treatment was randomly assigned at the block level to capitalize on permanently fenced areas to efficiently facilitate grazing and field operations, and within each block, crop sequence was replicated once at the plot level (5.5 m × 15 m; Figure S1).

2.3 | Experimental treatments

2.3.1 | Crop sequences

Eight 4-year crop sequences were compared (Table 1). All crop sequences were not represented in each year, but rather sequentially across the 4-year study, as has been done in similar research (e.g., Halde et al., 2015; Tiemann et al., 2015). Sequences included crops that are widely grown by organic farmers (e.g., spring wheat [*Triticum aestivum* L. emend. Thell.]) or are of interest in Montana and the broader NGP (e.g., hemp [*Cannabis sativa* L.]). In the final year of the study, all sequences were planted to spring wheat at a rate of 80 kg·ha^{-1} (240 live kernels·m^{-2}) to make grain yield comparisons.

Crop sequences were designed as a spectrum of crop growth/competition (i.e., estimated total number of growing days) and soil disturbance. Competitiveness was broadly defined by days of crop growth in the field: for annual crops, days of competition were calculated using the total days in the field from seeding date to termination date; for the perennial alfalfa, days of competition in year 1 were calculated from planting to a hard "killing" frost in the fall (day low temperature at or below −7°C), and, in years 2 and 3, estimated using a conservative start date of May 1 for FE and April 24 for the CARC and finished with final termination (Table 2). Crop sequences that were designed to have biennial sweet clover used the same estimates as alfalfa.

The alfalfa in sequence one (S1) was hayed or grazed once a season in mid-summer (mid to late June) at both locations, although when regrowth was sufficient, a second haying or grazing occurred at FE in late summer (mid-August). In the second sequence (S2), summer planted millet (*Setaria italica* L.) was planted in years 2 and 3 but did not germinate because seedbeds were dry. In sequences three (S3), four (S4), and six (S6), the biennial sweet clover was planted but did not establish due to damage from sweet clover weevil (*Sitona cylindricollis* Fahr.) and was replaced with field pea (*Pisum sativum* L.). The eighth sequence (S8 or "double fallow") constituted a tillage check where a year of wheat was followed by two consecutive years of high-frequency tillage (every 14–21 days; Table S2).

2.3.2 | Tillage treatments

FE—Standard-tillage

Primary spring tillage was done with a 4.4-m wide chisel plow equipped with 39-cm wide soil-inverting shovels at a depth of 10–15 cm, with rear-mounted tine harrows set in a relaxed position to minimize moving plant residues. Secondary tillage for final seedbed preparation was done with a 4.3-m wide vibra-shank field cultivator with 18-cm wide shovels at a depth of 10–15 cm without harrows. Primary post-harvest fall tillage was conducted with a chisel plow. If stubble needed to be chopped prior to plowing, it was done using a 4.5-m disk harrow with 5-cm notched disk blades on the front gang and 53-cm smooth disk blades on the rear gang set to a depth of 7–10 cm. In-season tillage for cover crop termination and fallow maintenance was accomplished using a 2.4-m wide toolbar with eight, 37-cm wide, soil-inverting shovels at a 15-cm soil depth. A forage harvester was used to terminate all non-grain crops.

FE—Reduced-tillage

Primary and secondary tillage were done using the implements described previously, either with 50% of the frequency or, once soil was loosened by a single pass of primary tillage, using three 85-cm wide non-inversion blades at a depth of 10 cm. Sheep (*Ovis aries*) grazing was used to terminate all non-grain crops.

CARC—Standard-tillage

Primary tillage in spring before planting consisted of inverting soil using a tandem disk with four 46-cm diameter notched disk blades comprising each of two front gangs set in perpendicular directions to travel at a 20° angle from the center, and two rear gangs of 46-cm diameter smooth disk blades set in perpendicular directions to travel at a 30° angle set from center and opposite the directions of the front gangs. The blades penetrated to an 11- to 13-cm soil depth. Secondary tillage

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TABLE 1 Crop sequences (1–8) with the associated crops, the years they were planted, and the seeding rate (kg·ha^{-1}). All eight crop sequences were planted to spring wheat in year 4 of the study. SW represents spring wheat, and CCM represents cover crop mixture.

Crop sequence	Crop	Scientific name	Years	Seeding rate (kg·ha^{-1})
1. Alfalfa	Barley	*Hordeum vulgare*	1	62.0
	Alfalfa	*Medicago sativa*	2, 3	13.5
2. Forage grains	Spring wheat	*Triticum aestivum*	1	80.0
	Triticale	x *Triticosecale*	2, 3	102.0
	Foxtail millet[a]	*Setaria italica*		5.6
3. SW-lentil-pea	Spring wheat	*Triticum aestivum*	1	80.0
	Lentil	*Lens culinaris*	2	41.5
	Sweet clover[a]	*Melilotus officinalis*		5.6
	Field pea	*Pisum sativum*	3	135.0
4. Lentil-SW-pea	Lentil	*Lens culinaris*	1	67.3
	Spring wheat	*Triticum aestivum*	2	80.0
	Sweet clover[a]	*Melilotus officinalis*		5.6
	Field pea	*Pisum sativum*	3	135.0
5. SW-double forage	Spring wheat	*Triticum aestivum*	1	80.0
	Barley	*Hordeum vulgare*	2	62.0
	Field pea	*Pisum sativum*	3	142.0
6. Lentil-pea-hemp	Lentil	*Lens culinaris*	1	67.3
	Sweet clover[a]	*Melilotus officinalis*		5.6
	Field pea	*Pisum sativum*	2	135.0
	Hemp	*Cannabis sativa* ssp. *sativa*	3	45.0
7. CCM-SW	Spring wheat	*Triticum aestivum*	2	80.0
	Barley	*Hordeum vulgare*	1, 3	6.7
	Emmer	*Triticum dicoccum*	1, 3	14.6
	Oats	*Avena sativa*	1, 3	7.8
	Field pea	*Pisum sativum*	1, 3	43.7
	Lentil	*Lens culinaris*	1, 3	7.8
	Faba bean	*Vicia faba*	1, 3	51.6
	Yellow mustard	*Sinapis alba*	1, 3	1.1
	Radish	*Raphanus sativus*	1, 3	5.6
	Turnip	*Brassica rapa* ssp. *rapa*	1, 3	1.1
8. Double fallow	Spring wheat	*Triticum aestivum*	1	80.0
	Tilled fallow		2, 3	N/A

[a]The sweet clover establishment failure resulted in annual field pea substitution the following year as a green manure.

consisted of cultivation and seedbed leveling to an 8- to 10-cm depth using 30-cm sweeps mounted onto S-tine shanks that were attached to two sections of an 0.8-m tool bar and spaced 22 cm apart on each section so that there was some overlap of soil disturbed by the two sections of shanks as tillage occurred. Post-harvest tillage consisted of a single pass using the tandem disk as already described.

CARC—Reduced-tillage

Primary tillage in spring consisted of undercutting the soil surface using a 1.5-m blade plow (i.e., noble blade) to a 7.6-cm depth when soil water content allowed penetration to occur in three passes per plot. In dry soils, the tandem disk described previously was adjusted so that front and rear gangs were oriented with disk blades set nearly parallel to the driving direction (≤10° from the center) and penetrating to an 8- to 10-cm depth, followed by use of the blade plow as described. Post-harvest tillage in non-grazed plots followed the procedure used in spring and was applied as needed for weed control, while sheep grazing was relied on to terminate non-grain crops and suppress weeds in forage plots. The blade plow was used as needed to suppress weeds in reduced-tillage fallow plots. The timing of tillage events for both FE and CARC can be found in Table S2.

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TABLE 2 Days of growth for crops in each cropping sequence at both study sites (Montana State University [MSU] Central Agricultural Research Center and MSU Fort Ellis Research Farm) for the first 3 years of the study, when competition differed among sequences (Y4 was wheat in all sequences). "Predicted" was an estimate of crop growth if all crops established and was used during experimental design. "Actual" are the realized days of crop growth in each sequence. Y1 represents year 1 of the crop sequence, Y2 represents year 2 of the crop sequence, and Y3 represents year 3 of the crop sequence. SW represents spring wheat, and CCM represents cover crop mixture.

Central Agricultural Research Center					
	Y1 (2019)	**Y2 (2020)**	**Y3 (2021)**	**Actual**	**Predicted**
Growth start date[a]	————	Apr 24	Apr 24	———	————
Last frost[b]	May 18	May 23	May 22	———	————
First frost	Sept. 28	Sept. 8	Sept. 17	———	————
First killing frost[c]	Oct. 1	Oct. 17	————	———	————
Consecutive frost-free days	133	108	118	359	————
Crop sequence					
1. Alfalfa[d]	74 (+ 65)	176	76	391	391
2. SW-cereal forage	132	63 (+51[e])	44 (+70[e])	239	360
3. SW-lentil-pea	132	84 (+68[f])	44 (76[f])	260	360
4. Lentil-SW-pea	116	98 (+54[f])	44 (76[f])	258	344
5. SW-double forage	132	63	44	239	239
6. Lentil-pea-hemp	116 (+24[f])	63 (87[f])	103	282	330
7. CCM-SW	75	98	72	245	245
8. Double fallow	132	0	0	132	132
Fort Ellis Research Farm					
	Y1 (2020)	**Y2 (2021)**	**Y3 (2022)**	**Actual**	**Predicted**
Growth start date[a]	————	May 1	May 1	———	————
Last frost[b]	May 11	Jun 6	May 23	———	————
First frost	Sept. 8	Sept. 17	Sept. 10	———	————
First killing frost[c]	Oct. 21	Nov. 7	————	———	————
Consecutive frost-free days	120	103	110	333	————
Crop sequence					
1. Alfalfa[d]	60 (+112)	190	58	420	420
2. SW-cereal forage	115	47 (+88[e])	60 (+47[e])	222	357
3. SW-lentil-pea	115	96 (+88[f])	60 (85[f])	271	384
4. Lentil-SW-pea	102	102 (+83[f])	60 (85[f])	264	355
5. SW-double forage	115	69	60	244	244
6. Lentil-pea-hemp	102 (+71[f])	69 (74[f])	95	266	342
7. CCM-SW	60	102	60	222	222
8. Double fallow	115	0	0	115	115

[a]Growth start date used to determine growing start dates for frost-hardy alfalfa and sweet clover after first establishment year.
[b]Last and first frosts determined by low temperature at or below 0°C (used as end date for frost-sensitive millet).
[c]Killing frost (low temperature at or below −6.67°C) used to determine end date for frost-hardy alfalfa and sweet clover growth for a season.
[d]Added value of barley nurse crop.
[e]Added anticipated value of millet crop had it successfully germinated and established.
[f]Added anticipated value of sweet clover crop had it successfully survived.

2.3.3 | Sampling methods

Data were collected using three 1-m^2 quadrats in 2019, six 0.5-m^2 quadrats in 2020–2022, and three 0.5-m^2 quadrats in 2023. All data were scaled to 1 m^2. Quadrat locations were stratified within plot such that one (2019, 2023) or two (2020–2022) quadrats were randomly assigned a location in each third of the plot, with a 1-m buffer from plot edges. Quadrats were placed perpendicular to crop rows, and three crop rows and four inter-row spaces were sampled. *Cirsium arvense* biomass sampling was performed with handheld sickles with plants cut at an 8-cm height from the soil surface and occurred prior to termination/harvest. *Cirsium arvense* stem counts were taken concurrently with biomass sampling.

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Biomass samples were dried after sampling at approximately 45°C for >72 h to a constant weight in the Montana State University Plant Growth Center. Once crops reached physiological maturity and had dried down, yields of grain were determined in subplots (interior five rows of each 20-row plot) using a small-plot combine and reported on a 120 g·kg^{-1} moisture basis.

2.4 | Statistical analysis

2.4.1 | *Cirsium arvense* temporal analysis

Cirsium arvense probability of occurrence was estimated using a logistic regression generalized linear mixed-effects model with a binomial distribution ("glmer," R-package "lme4"; Bates et al., 2015), with a response of presence/absence, fixed effects of tillage, crop sequence, year (numeric), all two-way interactions between the three variables, and the covariate of site to control for site variation, and random effects of plot nested in block. Once the logistic regression was complete, all subsequent *C. arvense* analyses were conducted on the aggregated plot data where *C. arvense* was found.

Cirsium arvense stem density (stems·m^{-2}) data were analyzed using a generalized linear mixed-effects model with a negative binomial distribution ("glmer.nb," R package "lme4"; Bates et al., 2015), with fixed effects of tillage, crop sequence, year (numeric), all two-way interactions between the three variables, and a covariate of site, and random effects of plot nested in block. A negative binomial distribution was used to alleviate statistical issues with overdispersion. *Cirsium arvense* biomass (g·m^{-2}) data were analyzed using a linear mixed-effects model ("lmer," R-package "lmerTest"; Kuznetsova et al., 2017) with the same fixed and random effects described above. *Cirsium arvense* biomass data were natural log transformed to meet assumptions of normality and constant variance. For all *C. arvense* temporal models, a quadratic term of year was used to satisfy the assumption of linearity.

2.4.2 | Final year analysis

In the final year, *C. arvense* probability of occurrence was again analyzed using a mixed-effects logistic regression model with fixed effects of crop sequence, tillage, site, and all two-way interactions between variables, and random effect of plot nested in block. Final *C. arvense* stem density and biomass analyses were completed using aggregated plot data from where *C. arvense* was found and followed the same methodology as their respective temporal analyses, but with fixed effects of sequence, tillage, site, and all two-way interactions among variables, with a random effect of block.

There were large differences in wheat grain yields between the two sites, therefore the wheat grain yield analysis was conducted separately for each site. Using plot level data, final wheat grain yield at CARC was analyzed using a linear model with predictors of tillage, sequence, and their interaction, with covariates of *C. arvense* biomass and block. Initially, a linear mixed-effects model with a random effect of block was used for the CARC analysis, but singularities resulted, forcing a linear model to be used with block as a predictor to account for the block variation. Fort Ellis plot level grain yield was analyzed using a linear mixed-effects model with grain yield as the response, fixed effects of crop sequence, tillage, and their interaction, with a random effect of block. Initially, the covariate *C. arvense* biomass was included in the FE model but was removed because it was insignificant. To satisfy assumptions of constant variance and normality, yield data were natural log transformed. The estimated marginal means of all final year response variables were calculated from their respective models and compared using Tukey post hoc comparisons ("emmeans" R-package "emmeans"; Lenth, 2023).

For all (temporal and final year) linear and linear mixed-effects models, extra-sum-of-squares *F*-tests were used for model refinement, and type-III *F*-tests were performed to determine if explanatory variables accounted for differences in *C. arvense* biomass and wheat grain yield. For generalized linear mixed-effects models, drop in deviance (likelihood ratio test) was used for model refinement, and type-III wald χ^2 tests were performed to determine if explanatory variables accounted for differences in *C. arvense* probability of occurrence and density ("Anova" in R package "car"; Fox & Weisberg, 2019). All analyses were conducted using the statistical software "R" (R Core Team, 2023).

3 | RESULTS

3.1 | *Cirisum arvense* probability of occurrence

There were no differences among *C. arvense* probability of occurrence for the different sequences in the first year of the study (Tables S3 and S4). Logistic regression analysis on *C. arvense* presence/absence data through time indicated an interaction between crop sequence and year for the probability of occurrence ($\chi^2 = 84.57$, $p < 0.001$; Table 3). As the study progressed, the probability of finding *C. arvense* diverged, with a decrease through time in sequence one (S1 with alfalfa) and an increase in all other sequences (Figure 1). During the fallow years (2, 3) of S8 (double fallow), *C. arvense* presence neared 0% of the quadrats, however, when S8 returned to crop production in year 4, *C. arvense* was found in almost 40% of quadrats.

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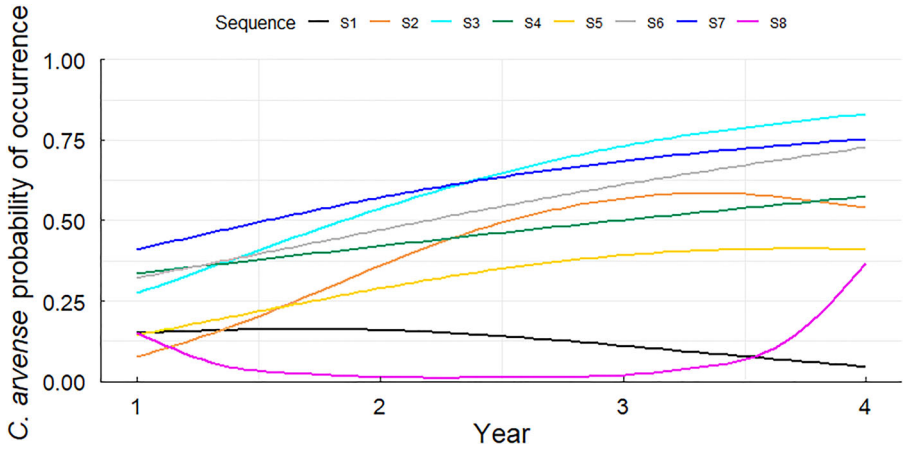


FIGURE 1 *Cirsium arvense* probability of occurrence in the eight crop sequences across the 4-year study. Slope estimates were back transformed from the final generalized linear mixed-effects logistic regression model. In ascending order, sequences S1–S8 represent alfalfa, spring wheat (SW)-cereal forage, SW-lentil-pea, lentil-SW-pea, SW-double forage, lentil-pea-hemp, cover crop mixture (CCM)-SW, and double fallow.

TABLE 3 Chi-square results with the associated degrees of freedom of the temporal logistic regression generalized linear mixed-effects model on *Cirsium arvense* presence/absence and the generalized linear mixed-effects negative binomial model on *C. arvense* stem density. "Poly(Year, 2)" represents the quadratic term of year used in the analysis.

Response	Explanatory	χ^2	*df*	*p* value
P/A	Sequence	16.70	7	**0.019**
	Poly(Year, 2)	53.31	2	**<0.001**
	Tillage	0.93	1	0.335
	Site	0.05	1	0.825
	Sequence: Poly(Year, 2)	84.57	14	**<0.001**
Stem density	Sequence	20.33	7	**0.005**
	Poly(Year, 2)	50.25	2	**<0.001**
	Tillage	1.11	1	0.292
	Site	0.36	1	0.549
	Sequence: Poly(Year, 2)	47.59	14	**<0.001**
	Sequence: Tillage	16.02	7	**0.025**

TABLE 4 Chi-square results for the final year logistic regression generalized linear mixed-effects model on *Cirsium arvense* presence/absence and the generalized linear mixed-effects negative binomial model on *C. arvense* stem density.

Response	Explanatory	χ^2	*df*	*p* value
P/A	Sequence	51.69	7	**<0.001**
	Tillage	3.07	1	0.080
	Site	0.32	1	0.575
Stem density	Sequence	31.19	7	**<0.001**
	Tillage	0.66	1	0.418
	Site	5.45	1	**0.020**

In the final year, an effect of crop sequence on *C. arvense* probability of occurrence was detected ($\chi^2 = 51.69, p < 0.001$; Table 4). The probability of occurrence was lowest in S1, with C. *arvense* being found in ~15% of S1 quadrats, differing from all other crop sequences except S8, where it was estimated to be found in ~39% of quadrats (Figure 2A).

3.2 | *Cirsium arvense* stem density

There were no differences in *C. arvense* stem densities among crop sequences in the first year of the study (Tables S3 and S5). Through time, an interaction was detected between crop sequence and year for stem density in plots where *C. arvense* occurred ($\chi^2 = 47.59$, $p < 0.001$; Table 3). For all sequences except S8 (double fallow), stem density through time demonstrated a unimodal response, with higher values in years 2 and 3 than in years 1 and 4 (Figure 3). Stem density in S8 decreased through time, with the largest annual decrease after year 1. Besides S8, the only other sequence to have a decrease in stem densities across the study was S1 (with alfalfa), which had a muted unimodal response and the lowest stem density value in the fourth year. There was an interaction between crop sequence and tillage on *C. arvense* stem density ($\chi^2 = 16.02$, $p = 0.025$; Table 3). The impact of this interaction was evident in higher values in the S1 reduced tillage (20.11 ± 9.26) compared with S1 standard tillage (5.52 ± 2.48, $p = 0.034$), and S5 reduced tillage (46.89 ± 19.13) compared with S5 standard-tillage (10.09 ± 4.10, $p = 0.005$).

In the final year, stem densities differed among the crop sequences in plots where *C. arvense* was found ($\chi^2 = 31.19$, $p < 0.001$; Table 4). Mean stem density of S1 was lower than mean stem densities of all other crop sequences except S8, with S8 also differing from S6 and S7 (Figure 2B). Stem densities differed between the two sites, with CARC (7.69 ± 1.89)

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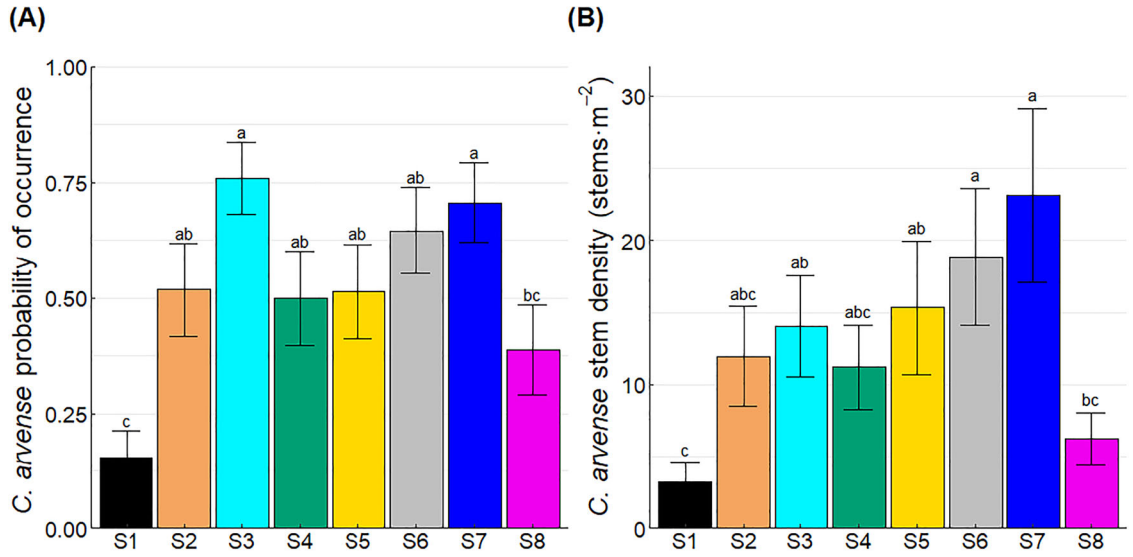


FIGURE 2 Final year estimated marginal means (±SE) in each crop sequence for (A) *Cirsium arvense* probability of occurrence and (B) *C. arvense* stem density (stems·m^{-2}). Estimated marginal means were back transformed from their respective generalized linear mixed-effects models, and letters above the error bars indicate differences between means ($p < 0.05$). In ascending order, sequences S1–S8 represent alfalfa, spring wheat (SW)-cereal forage, SW-lentil-pea, lentil-SW-pea, SW-double forage, lentil-pea-hemp, cover crop mixture (CCM)-SW, and double fallow.

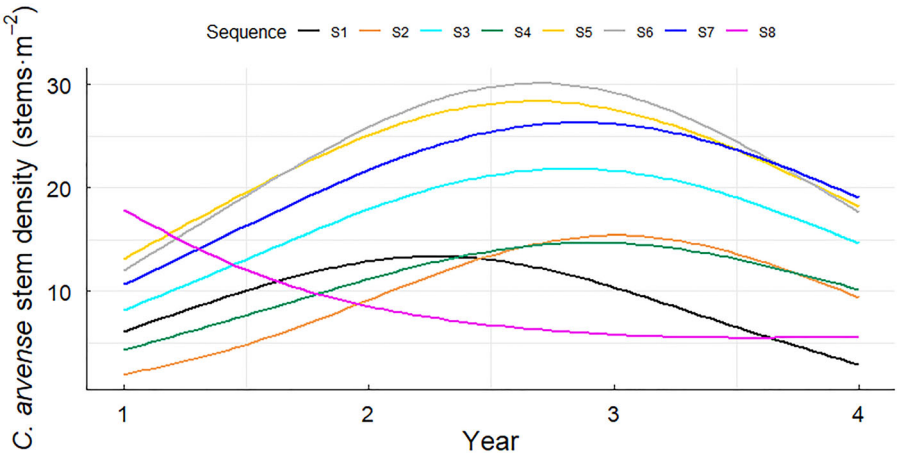


FIGURE 3 *Cirsium arvense* stem density in eight crop sequences across the 4-year study. Slope estimates were back transformed from the final generalized linear mixed-effects model with a negative binomial distribution. In ascending order, sequences S1–S8 represent alfalfa, spring wheat (SW)-cereal forage, SW-lentil-pea, lentil-SW-pea, SW-double forage, lentil-pea-hemp, cover crop mix (CCM)-SW, and double fallow, with spring wheat across all eight studies in the fourth year.

having a lower mean stem density than FE (16.38 ± 3.59; $\chi^2 = 5.45$, $p = 0.020$).

3.3 | *Cirsium arvense* biomass

There were no differences in *C. arvense* biomass among crop sequences in the first year of the study (Tables S3 and S6). In the temporal analysis, an interaction was detected between crop sequence and year ($F_{(14,\ 189.09)} = 2.06$, $p = 0.016$), but there was no evidence of an effect of tillage ($F_{(1,65.37)} = 0.96$, $p = 0.332$) on *C. arvense* biomass. As with stem density, *C. arvense* biomass demonstrated a hump-shaped response across the 4 years of the study in six of the crop sequences, with S1 (with alfalfa) and S8 (double fallow) demonstrating declines over the course of the study (Figure 4). There was also a site effect and, when averaged across crop sequences, tillage treatments, and years, CARC (11.9 ± 2.7 g·m^{-2}) had lower *C. arvense* biomass than FE (42.7 ± 10.3 g·m^{-2}; $F_{(1,65.25)} = 19.70$, $p < 0.001$).

Final year analysis demonstrated a difference in the *C. arvense* biomass between the two sites, with considerably less biomass at CARC (4.2 ± 1.5 g·m^{-2}) than FE (126.1 ± 39.8 g·m^{-2}; $F_{(1,8.42)} = 51.12$, $p < 0.001$). There

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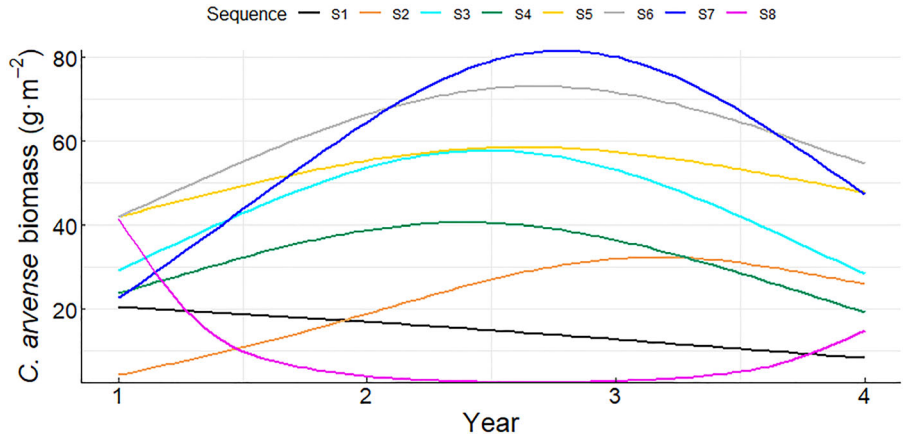


FIGURE 4 *Cirsium arvense* biomass in eight crop sequences across the 4-year study. Slope estimates were back transformed from the final linear mixed-effects model. In ascending order, sequences S1–S8 represent alfalfa, spring wheat (SW)-cereal forage, SW-lentil-pea, lentil-SW-pea, SW-double forage, lentil-pea-hemp, cover crop mixture (CCM)-SW, and double fallow.

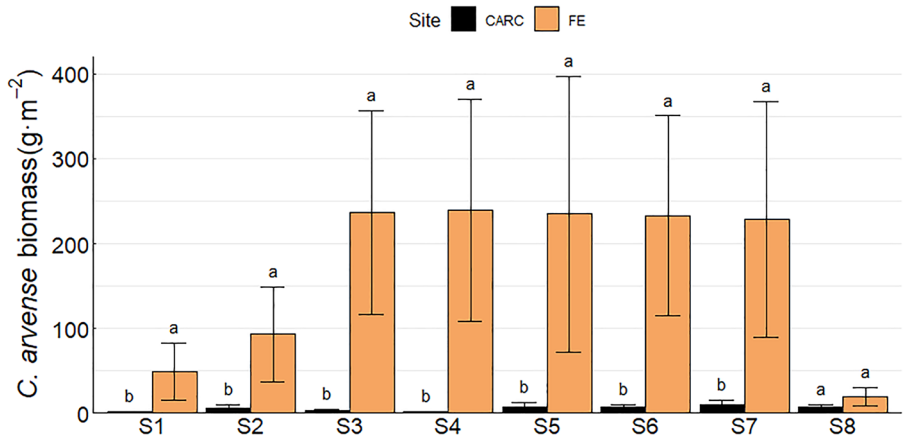


FIGURE 5 Final year *Cirsium arvense* biomass ($g \cdot m^{-2}$) estimated marginal means (± SE) in each crop sequence for the Central Agricultural Research Center (CARC) and Fort Ellis Research Farm (FE) study sites. Estimated marginal means were back transformed from the final year *C. arvence* biomass linear mixed-effects model, and letters above the error bars indicate differences between sites within each sequence ($p < 0.05$). In ascending order, sequences S1–S8 represent alfalfa, spring wheat (SW)-cereal forage, SW-lentil-pea, lentil-SW-pea, SW-double forage, lentil-pea-hemp, cover crop mixture (CCM)-SW, and double fallow.

was also an interaction between site and crop sequence on *C. arvense* biomass ($F_{(7,57.50)} = 3.25$, $p = 0.006$). Fort Ellis had higher estimated *C. arvense* biomass than CARC for all sequences, except S8 (double fallow), which demonstrated no difference between CARC and FE values (Figure 5). There was only one significant difference between mean *C. arvense* biomass values among the sequences at CARC, with S4 (1.5 ± 0.7 $g \cdot m^{-2}$) having less biomass than S7 (10.3 ± 5.3 $g \cdot m^{-2}$; $p = 0.025$). At FE, *C. arvense* biomass was lower in S8 (19.8 ± 10.9 $g \cdot m^{-2}$) than S3 (236.9 ± 119.8 $g \cdot m^{-2}$; $p = 0.009$), S4 (239.0 ± 131.3 $g \cdot m^{-2}$; $p = 0.015$), S6 (232.8 ± 117.8 $g \cdot m^{-2}$; $p = 0.009$), and S7 (229.0 ± 139.1 $g \cdot m^{-2}$; $p = 0.029$). In contrast to crop sequence, there were no significant interactions that included tillage, nor did estimated *C. arvense* biomass differ between tillage treatments ($F_{(1,57.70)} = 2.17$, $p = 0.146$).

3.4 | Final year wheat grain yield

Wheat grain yield was considerably lower at CARC (380 ± 175 $kg \cdot ha^{-1}$) than FE (1510 ± 975 $kg \cdot ha^{-1}$). At CARC, after accounting for the effect of the covariate *C. arvense* biomass, tillage ($F_{(1)} = 26.41$, $p < 0.001$), sequence ($F_{(7)} = 6.74$, $p < 0.001$), and their interaction affected grain yield ($F_{(7)} = 4.76$, $p < 0.001$). Sequence one (S1 with alfalfa) grain yield was lower in the standard-tillage (10.20 ± 2.63 $kg \cdot ha^{-1}$) compared to the reduced-tillage (61.40 ± 15.57 $kg \cdot ha^{-1}$; $p < 0.001$). Among sequences, S1 had lower yields than the other sequences in both tillage treatments (Figure 6). The only other difference among grain yields at CARC was a higher grain yield in S8 (double fallow) compared with S3 in the standard-tillage plots.

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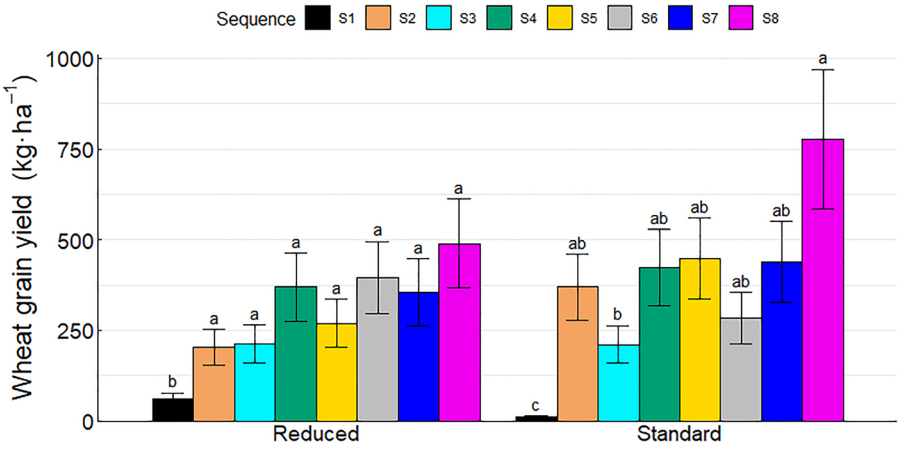


FIGURE 6 Central Agricultural Research Center (CARC) wheat grain yield (kg·ha^{-1}) estimated marginal means (± SE) for each crop sequence in the reduced- and standard-tillage treatments. Estimated marginal means were back transformed from the final year wheat grain yield linear model, and letters above the error bars indicate differences among sequences within each tillage treatment ($p < 0.05$). In ascending order, sequences S1–S8 represent alfalfa, spring wheat (SW)-cereal forage, SW-lentil-pea, lentil-SW-pea, SW-double forage, lentil-pea-hemp, cover crop mixture (CCM)-SW, and double fallow.

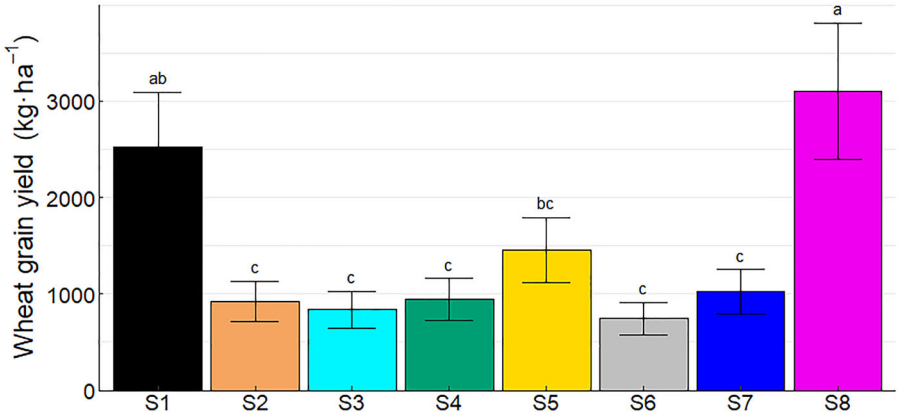


FIGURE 7 Fort Ellis Research Farm (FE) wheat grain yield (kg·ha^{-1}) estimated marginal means (±SE) for each crop sequence. Estimated marginal means were back transformed from the final year wheat grain yield linear mixed-effects model, and letters above the error bars indicate differences among sequences ($p < 0.05$). In ascending order, sequences S1–S8 represent alfalfa, spring wheat (SW)-cereal forage, SW-lentil-pea, lentil-SW-pea, SW-double forage, S6 lentil-pea-hemp, cover crop mixture (CCM)-SW, and double fallow.

Fort Ellis wheat grain yield differed among sequences ($F_{(7,35)} = 10.16$, $p < 0.001$). Wheat grain yield was highest in S1 and S8, with S8 having higher wheat grain yield than six other sequences (it did not differ from S1), while S1's grain yield was higher than all sequences except S8 and S5 (Figure 7). There were no other differences in wheat grain yield among the sequences.

4 | DISCUSSION

The temporal trends of the alfalfa sequence and two of the three final year responses (probability of occurrence and stem density) provided support for the hypothesis that perennial forage crops provide better *C. arvense* suppression than crop sequences composed of annual species. Similarly, *C. arvense* stem density and biomass temporal trends, along with final year biomass, supported the hypothesis that multiple years of intensively managed fallow suppressed *C. arvense* compared with crop sequences consisting of annual species. Reduced-tillage only had higher *C. arvense* stem density compared with standard-tillage for two crop sequences (S1, S5), providing little evidence that standard-tillage would enhance weed suppression (our second hypothesis). Evidence supporting the third hypothesis, that final-year wheat grain yield would be inversely related to crop sequence competition, was site dependent. At CARC, wheat grain yield increased following consecutive years of fallow and yield depression occurred when wheat followed alfalfa, as expected, especially when standard-tillage practices were used. However, FE yields were

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highest when final-year wheat followed consecutive years of fallow or alfalfa, with no observed yield depression after alfalfa even when standard-tillage practices were used.

Perennial forage crop sequences are a tactic used by some organic producers to provide weed suppression, and, consistent with our findings, incorporating a multi-year competitive perennial forage like alfalfa can suppress *C. arvense* (Favrelière et al., 2020; Gramig et al., 2024). Alfalfa grows quickly with leaf structural attributes that maximize photosynthesis and leaf area (Dincă & Dunea, 2018), creating a canopy that can interfere with light interception by *C. arvense* (Gramig et al., 2024). Early canopy closure from alfalfa can stunt growth and hinder photosynthesis of *C. arvense* and other shade-intolerant species, thereby reducing root growth and flower formation by the weed (Tiley, 2010). Belowground, root system size and overlap influence the competitive interaction of neighboring species (Bartelheimer et al., 2008), and, as a deep-rooted perennial species, alfalfa's rooting structure is more similar to *C. arvense* than annual crops, increasing overlap and competitive interference.

The agronomic management of alfalfa likely increases its effectiveness as a cultural management tool for *C. arvense*. Removal or termination events (e.g., grazing, mowing) associated with growing alfalfa and other forages disrupt the growth of *C. arvense* and can reduce populations (Bourdôt et al., 2016; Lukashyk et al., 2008), likely due to depleting stored root carbohydrates, which are used for regenerative shoot growth after these events (Graglia et al., 2006). Alfalfa has faster regrowth after a removal event than many perennial species (Meiss et al., 2010) and, coupled with the negative impact on growth of these events, can give alfalfa a competitive advantage over *C. arvense* for growth resources.

The crop sequence that included a double (i.e., 2 year) fallow phase provided better control of *C. arvense* than sequences with higher annual crop competition and less frequent tillage. Consistent with previous research, these results indicate that it is the frequency more than the intensity of mechanical soil disturbance that impacts growth and persistence of this weed species (Lehnhoff et al., 2017; Tiley, 2010). Interestingly, in the wheat cash crop that followed the double fallow sequence, *C. arvense* occurred in more sampling quadrats than in the year prior to the double fallow phase. This observation suggests that double fallow management (i.e., high frequency tillage) either facilitated the expansion of *C. arvense* in the subsequent cash crop, which has been previously observed (Stolcova, 2002), or failed to slow its natural spread. Still, the double fallow phase weakened the *C. arvense* population (lower density and biomass) over the course of the study, decreasing its impact on subsequent production and likely making it more susceptible to future control efforts.

Livestock grazing was a component of the reduced-tillage system in this study. Livestock-integrated systems in the NGP have proven benefits in tillage reduction, improved soil quality, nutrient cycling, and expanded economic capabilities, while having variable results as a weed management tool (Larson et al., 2021, 2024; McKenzie et al., 2017; Sainju et al., 2010). Our findings did not provide evidence that standard tillage practices were better for *C. arvense* management than reduced tillage, characterized by sheep grazing. As the goal of semiarid organic farming is to reduce tillage due to its effects on soil health and soil moisture, this lack of result is encouraging and may indicate that reduced-tillage methods, featuring high-intensity but low-frequency sheep grazing, can be used in lieu of standard-tillage practices for forage crop removal and control of *C. arvense* in semiarid organic cropping. This is consistent with previous research where suppression of *C. arvense* resulted using high-intensity, low-frequency grazing with cattle (*Bos taurus*; De Bruijn & Bork, 2006). Our results, and those of previous research, suggest that future work is needed to determine how reduced-tillage practices impact *C. arvense* management in different environments. Meanwhile, our findings should be approached with caution by farmers.

In dryland farming, plant-available water is the most important factor that limits production, and water drawdown by the preceding crop(s) impacts subsequent crop production (Hansen et al., 2012). This effect is magnified when growing days of the preceding crop are maximized with perennial forage crop growth (Cutforth et al., 2010). This impact makes rotating perennial forages with cash grain crops challenging and potentially less successful in semiarid than in subhumid regions (Delate et al., 2013). Results of the current study demonstrate the difficulty of preceding cash grain crops with perennial forages in dry environments. The limited precipitation (annual precipitation at CARC was ~200 mm less than FE in year 4 of our study) and lower soil water holding capacity of the soils at CARC (Sigler et al., 2020) compared to FE resulted in a significant reduction in wheat grain production. This effect was magnified when wheat followed alfalfa, especially when standard-tillage practices were used, which also reduces soil water storage (Burgess et al., 2014). Conversely, wheat grain yield was highest in the alfalfa and double fallow sequences at FE, the two sequences that provided the best control of *C. arvense*, suggesting that optimizing subsequent cash crop performance and suppressing *C. arvense* using an alfalfa forage phase is possible in some semiarid environments.

This study demonstrates the relative effectiveness of a perennial forage in combination with annual crops, or consecutive years of tilled fallow, in managing the challenging weed *C. arvense*. However, the study had limitations. We used an approach where various crop sequences were followed through time with a final year cash crop check, as opposed to growing each crop of the sequences each year. Using this sequential approach, the interannual variation confounds and occludes the effects that the specific crops have on the *C. arvense* responses. Another limitation was the high variation of *C. arvense* across crop sequence treatments. Weed density

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was patchy at both sites, resulting in more *C. arvense* in some plots than in others. This nonuniformity in weed density was addressed using random effects and by first evaluating *C. arvense* presence-absence, and subsequently evaluating stem density and biomass responses where *C. arvense* occurred. Still, variation of many of the responses remained large, thus reducing the strength of evidence supporting our results. Using permanent frame locations and sampling a larger area within each plot might have reduced the variation and added strength to our results and should be considered in future research.

5 | CONCLUSION

Different cultural (i.e., crop sequences) and mechanical (i.e., tillage) practices for *C. arvense* management in semiarid organic cropping were compared in this study. Results demonstrated that a deep-rooted, perennial crop (i.e., alfalfa) that was terminated using sheep grazing, or multiple years of intensively managed fallow, can be used in sequence as a part of a semiarid organic weed management plan for *C. arvense*. However, perennial forage crop sequences with annual crops can come at a cost in subsequent cash crop production, especially when soil moisture is limiting. In this instance, a year of fallow following perennial forage growth is recommended for soil moisture recharge. Future research should explore integration of perennial forage crops followed by a year of fallow and then multiple years of annual crop production to determine the temporal effect/legacy of perennial forage and fallow on *C. arvense* populations and cash crop production.

AUTHOR CONTRIBUTIONS

Christian D. Larson: Data curation; formal analysis; investigation; supervision; visualization; writing—original draft; writing—review and editing. **Kara Hettinger**: Data curation; investigation; writing—original draft; writing—review and editing. **Patrick M. Carr**: Conceptualization; funding acquisition; investigation; methodology; project administration; supervision; writing—review and editing. **Perry R. Miller**: Funding acquisition; investigation; methodology; supervision; writing—review and editing. **McKenna Volkman**: Investigation; writing—review and editing. **Daniel Chichinsky**: Data curation; investigation; writing—review and editing. **Tim Seipel**: Conceptualization; funding acquisition; investigation; methodology; project administration; supervision; writing—review and editing.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

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

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