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Weed community structure and soybean yields in a long-term organic cropping systems experiment

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Abstract

Weed management is a major challenge in organic crop production, and organic farms generally harbor larger weed populations and more diverse communities compared with conventional farms. However, little research has been conducted on the effects of different organic management practices on weed communities and crop yields. In 2014 and 2015, we measured weed community structure and soybean [*Glycine max* (L.) Merr.] yield in a long-term experiment that compared four organic cropping systems that differed in nutrient inputs, tillage, and weed management intensity: (1) high fertility (HF), (2) low fertility (LF), (3) enhanced weed management (EWM), and (4) reduced tillage (RT). In addition, we created weed-free subplots within each system to assess the impact of weeds on soybean yield. Weed density was greater in the LF and RT systems compared with the EWM system, but weed biomass did not differ among systems. Weed species richness was greater in the RT system compared with the EWM system, and weed community composition differed between RT and other systems. Our results show that differences in weed community structure were primarily related to differences in tillage intensity, rather than nutrient inputs. Soybean yield was lower in the EWM system compared with the HF and RT systems. When averaged across all four cropping systems and both years, soybean yield in weed-free subplots was 10% greater than soybean yield in the ambient weed subplots that received standard management practices for the systems in which they were located. Although weed competition limited soybean yield across all systems, the EWM system, which had the lowest weed density, also had the lowest soybean yield. Future research should aim to overcome such trade-offs between weed control and yield potential, while conserving weed species richness and the ecosystem services associated with increased weed diversity.

Introduction

Weed management in organic crop production is a major challenge (Baker and Mohler 2015; Bàrberi 2002). Organic grain crop farmers often rely heavily on mechanical weed control, which varies in effectiveness based on weather and soil moisture conditions (Bond and Grundy 2001). In many cases, organic farmers augment mechanical weed control practices with cultural practices that reduce weed populations and weed–crop competition (Bastiaans et al. 2008). Despite this integrated approach, competition from weeds is one of the main factors responsible for the yield gap between organic and conventional production (Kravchenko et al. 2017). For example, Cavigelli et al. (2008) reported that weed competition was the second most important factor after low nitrogen availability that prevented organic corn (*Zea mays* L.) yields from matching conventional corn yields in the long-term Farming Systems Project (FSP) in Maryland. In subsequent research, weeds were shown to have a greater effect on corn yield and nitrogen to have a lesser effect under dry conditions (Teasdale and Cavigelli 2010). In soybean [*Glycine max* (L.) Merr.], which forms a symbiotic relationship with bacteria that fix atmospheric nitrogen, the yield gap between organic and conventional is often almost entirely due to weed competition. For example, in the FSP, soybean yields were on average 19% lower in the organic systems compared with conventional systems, a difference that was attributed solely to weeds (Cavigelli et al. 2008).

Mechanical and cultural weed management practices (e.g., soil tillage, crop rotation) and the approach that farmers use to manage nutrients can also affect weed communities and weed species diversity (Ryan et al. 2010b). For example, Gruber and Claupein (2009) reported that both weed seedbank density and weed density were greater in organic plots managed with chisel-plow tillage compared with moldboard-plow tillage. Reducing tillage can also facilitate a shift in weed communities toward perennial species (Ryan et al. 2009a; Thomas et al. 2004), which can be more difficult to control in organic production (Gallandt 2014). Secondary cultivation and other weed management practices performed after the crop has emerged can affect weed communities. For instance, rotary hoeing and tine harrowing have been shown to be more effective against shallow-rooted weeds such as giant foxtail (*Setaria faberi* Herrm.) and common chickweed [*Stellaria media* (L.) Vill.] compared with weed species capable of emerging from greater depths such as velvetleaf (*Abutilon theophrasti* Medik.) and wild oat (*Avena fatua* L.) (Gunsolus 1990). Flame weeding has been shown to be more effective against broadleaf weeds such as common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), and *A. theophrasti* compared with grass weed species such as large crabgrass [*Digitaria sanguinalis* (L.) Scop.] and *S. faberi* (Taylor et al. 2012). In addition to mechanical and thermal weed control practices, the form in which nutrients are supplied can affect weed growth (Blackshaw et al. 2003; Davis and Liebman 2001; Little et al. 2015) and weed community composition (Menalled et al. 2001). Thus, understanding the effects of different management practices on weed community structure (i.e., weed abundance and community composition) is important for developing robust organic weed management strategies.

Typically, weeds are more abundant and weed communities are more diverse in organic cropping systems compared with conventional cropping systems, where synthetic herbicides are used (Hole et al. 2005; Kremen and Miles 2012; Menalled et al. 2001; Ryan et al. 2010b; Wortman et al. 2010). The agroecological consequences of increased weed species diversity are not well understood. On one hand, increased weed species diversity in organic cropping systems may help to promote ecosystem services such as pollination (Bretagnolle and Gaba 2015; Holzschuh et al. 2008), biological control of crop pests (Norris and Kogan 2000), and regeneration of soil health (Smith et al. 2011; Sturz et al. 2001). On the other hand, increased weed diversity may pose additional challenges for organic farmers, as different weeds might require different management practices for effective suppression. Previous research has reported both negative (Davis et al. 2005) and neutral (Pollnac et al. 2009) relationships between weed species density and crop yield. In other research examining crop yield loss, Storkey and Neve (2018) reported a strong negative relationship between weed species richness and crop yield loss in winter wheat (*Triticum aestivum* L.) and hypothesized that more diverse weed communities will be less competitive with crops due to phenotypic differentiation between the weeds and the crop. Hence, there remains a need to better understand how crop yields respond to both the abundance and diversity of the weed community under different forms of weed management.

We conducted a nested experiment within the long-term Cornell Organic Grain Cropping Systems Experiment (OCS) in central New York State to evaluate the impact of different organic grain management practices on weed community structure and soybean performance. We expected that different approaches to organic grain crop management would result in quantifiably distinct weed communities and that these differences in weed community structure would be associated with differences in soybean yield. Specifically, we hypothesized that (1) a cropping system with greater nutrient inputs would have greater weed abundance compared with systems with lower nutrient inputs, (2) perennial weed species would dominate the weed community in a cropping system with reduced soil tillage compared with systems with increased soil tillage and cultivation, and (3) soybean yield would be greatest in a cropping system with additional soil tillage and cultivation compared with systems with fewer weed management operations.

Materials and Methods

Long-Term Experiment

The OCS experiment was initiated in 2005 at the Cornell University Musgrave Research Farm in Aurora, NY, USA (42.73°N, 76.66°W). The soil was a moderately well-drained, calcareous Lima silt loam (fine-loamy, mixed, semiactive, mesic Oxyaquic Hapludalfs) with partial tile drainage and pH near 7.8. The experiment compared four organic cropping systems that varied in nutrient inputs, weed management, and tillage practices. The experimental design was a split-plot randomized complete block design with four replications. Cropping system (described in the following section) was the whole-plot factor and crop rotation entry point was the split-plot factor. Two crop rotation entry points were used so that two crops were represented in each system each year. Split plots measured 9.1 by 30.5 m (12.2 by 36.6 m including borders).

Cropping Systems

The four cropping systems were managed based on distinct guiding principles throughout the duration of the long-term experiment (2005 to 2015), though specific management practices varied slightly over time. The high-fertility (HF) system received multiple nutrient inputs, including legume green manures, composted chicken manure, and commercial organic fertilizers (Table 1). In contrast, fertility in the low-fertility (LF) system was supplied nearly exclusively by legume green manures. Both the HF and LF systems received intermediate levels of weed management through tillage and cultivation (Table 1). The enhanced weed management (EWM) system received supplemental weed management, mainly additional tillage and cultivation. The reduced-tillage (RT) system received less frequent and less intense tillage operations than other systems. Both the EWM and RT systems were fertilized at intermediate levels (Table 1). The entire field site was managed using organic practices and was certified by the Northeast Organic Farming Association of New York. For a detailed description of management practices used from 2005 to 2010, see Caldwell et al. (2014).

Several changes were made to OCS management practices in 2011 to address emerging agronomic challenges. From 2005 to 2010, all four cropping systems had the same 3-yr rotation of corn–soybean–winter spelt/red clover (*Triticum spelta* L./*Trifolium pratense* L.). During this time, weed abundance increased in the HF and RT systems due to high nutrient inputs (HF) and inadequate mechanical control (RT) (Caldwell et al. 2014). Consequently, the crop sequence in the HF and RT was changed in 2011 to a 6-yr rotation of corn–soybean–winter spelt–winter barley/buckwheat (*Hordeum vulgare* L./*Fagopyrum esculentum* Moench)–soybean–winter spelt/red clover to vary the timing of tillage in these systems and disrupt weed life cycles. The LF and EWM systems maintained the original crop rotation (Table 1). Also in 2011, an experimental ridge tillage practice in the RT system was replaced by a combination of chisel-plow and deep zone tillage (Table 1) to provide better mechanical weed control. Starting in 2011, we applied compost to spelt in the EWM system and increased spelt seeding rates (to match the EWM rate) in all systems as an additional cultural weed control practice (Table 1).

Table 1. Primary management differences across the four cropping system treatments in the Cornell Organic Grain Cropping Systems Experiment, Aurora, NY, USA, 2011–2015.[a]

	High fertility	Low fertility	Enhanced weed management	Reduced tillage
Crop rotation[b]	C/r-S-SP-B/BU-S-SP/c	C-S-SP/c	C/r-S-SP/c	C-S-SP-B/BU-S-SP/op
Fertility inputs[c]				
Compost[d] (Mg ha^{-1})	3.4 (B), 1.1 (SP)	—	1.1 (SP)	3.4 (B), <2 (C)
P, K[e]	Varied (C, SP)	—	—	—
Tillage[f]				
Moldboard plow	C, S, SP, B, BU	C, S	C, S, SP	—
False seedbed	—	—	S (if possible)	—
Deep zone till	—	—	—	C
Chisel plow	—	—	—	S, SP, B, BU
Weed control[g]				
Tine harrow	1–3	1–3	1–3	—
Interrow cultivator[h]	1–4	1–4	2–5	1–3

[a] Abbreviations: C, corn; S, soybean; SP, spelt; B, winter barley; BU, buckwheat; r, annual ryegrass [*Lolium perenne* (L.) ssp. *multiflorum* (Lam.) Husnot]; c, red clover (*Trifolium pretense* L.); op, oat (*Avena hybrida* Peterm. ex Rchb.)/Austrian winter pea (*Pisum sativum* L.) mix.

[b] Crop rotation was C-S-SP/c in all systems before 2011. See Caldwell et al. (2014) for additional information about management during first two rotation cycles.

[c] Application rates per season. All systems received low-analysis starter fertilizer on corn.

[d] Composted poultry manure (5-5-3 N-P_2O_5-K_2O, Kreher's Enterprises, Clarence, NY, USA). Rates assume 14% moisture. Enhanced weed management (EWM) did not receive compost before 2011. Reduced tillage received variable compost when necessary to supplement inadequate legume nitrogen.

[e] Organic fertilizers applied based on phosphorus and potassium soil tests.

[f] Tillage practices by crop. All systems also used secondary tillage (disk, roller harrow).

[g] Events per season in corn and soybean.

[h] Two passes per year were most common except in EWM, where three passes were most common.

Table 2. Dates of management practices in the nested experiment (2014–2015).[a]

	2014				2015			
	HF	LF	EWM	RT	HF	LF	EWM	RT
Moldboard plow	May 20	May 27	May 20	—	May 26	May 26	May 4	—
Chisel plow	—	—	—	May 20	—	—	May 27[c]	May 27[d]
Disk	May 27	May 27	May 27	May 27	June 4	June 4	May 4	June 4
Field cultivator	—	—	—	—	—	—	June 4	—
Roller harrow[b]	May 30	May 30	May 28 May 30	May 30	June 5	June 5	May 4 June 5	June 5
Crop planting	May 30	May 30	May 30	May 30	June 5	June 5	June 5	June 5
Tine harrow	June 6	June 6	June 6	June 6	—	—	—	—
Interrow cultivator	June 16 June 20 July 2	June 16 June 20 July 2	June 16 June 20 July 2 July 23	June 16 June 20 July 2	June 25 July 6 July 17	June 25 July 6 July 17	June 25 July 6 July 17 July 31	June 25 July 6 July 17

[a] Systems and years: EWM, enhanced weed management; HF, high fertility; LF, low fertility; RT, reduced tillage. 2014, entry point A; 2015, entry point B.

[b] With or without roller-harrow tines engaged depending on residue.

[c] Chisel plow was used in EWM in 2015 to disrupt rhizomatous perennial weeds.

[d] Chisel plow was used two times in RT in 2015.

Nested Experiment

In 2014 and 2015, a nested experiment was conducted in the soybean phase of each crop rotation entry point. Soybean followed buckwheat (HF, RT) or corn (LF, EWM) in both years of the nested experiment. Soybean 'Dares' (relative maturity 0.8, food grade, imperfect yellow hilum; Butterworks Farm, Westfield, VT, USA) was inoculated with N-Dure™ (*Bradyrhizobium japonicum*, INTX Microbials, Kentland, IN, USA) and planted in 76-cm rows at 642,000 seeds ha^{-1} (2014) or 715,000 seeds ha^{-1} (2015) using a four-row planter (John Deere, Moline, IL, USA). Soybean seeding rates were higher than conventional rates in order to hasten crop canopy closure and suppress weeds.

Weed Infestation Treatments

Two weed infestation treatments, ambient weed (AW) and weed-free (WF), were implemented in subplots (3.0 by 6.1 m) that were randomly located in each soybean main plot. AW subplots received standard soybean management practices for the systems in which they were located (Table 2). WF subplots were hand weeded every 1 to 2 wk from June 27 to August 7 (2014) and July 2 to August 6 (2015) in addition to receiving standard weed management practices.

Sampling

Biomass and Density

Soybean and weed aboveground biomass in each subplot were sampled in two 0.25-m^2 quadrats (76 by 33 cm) on August 18 (2014) and August 14 to 15 (2015). All stems rooted in the quadrat were clipped at soil level, separated by species, counted, oven-dried at 40 C for at least 2 wk, and weighed. Data from the two quadrats in each subplot were averaged before analyses.

Soybean Yield

Soybeans were harvested on October 6 (2014) and October 7 to 8 (2015) from the inner two rows of each subplot using a plot

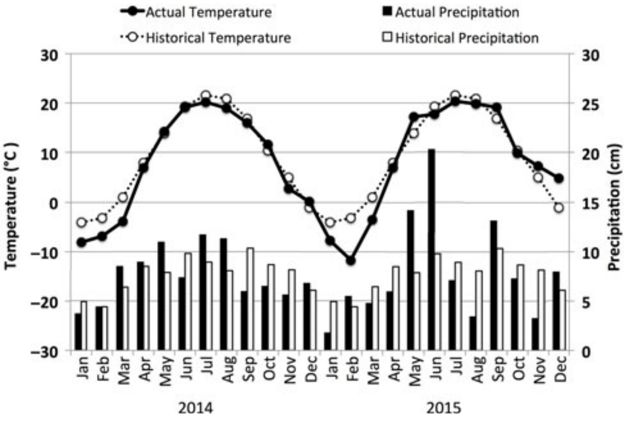

Figure 1. Monthly average temperature (lines) and total precipitation (bars) at the Musgrave Research Farm in Aurora, NY, USA (42.73°N, 76.66°W), 2014–2015. Actual conditions (solid, black) are shown beside 30-yr historical averages (dotted, white). Data were accessed through the Northeast Regional Climate Center database (http://climod.nrcc.cornell.edu).

combine that measured grain mass and moisture content (Almaco, Nevada, IA, USA). Soybean grain yields were standardized before analyses (g m^{-2} at 13% moisture), accounting for the area where soybean plants were removed during previous sampling (i.e., biomass quadrats).

Data Analysis

Weed Abundance and Community Composition

Weed species richness and evenness were calculated in each AW subplot. Richness was determined as the number of weed species present per 0.5 m^{-2}. Evenness describes the relative allocation of weed biomass or weed density among species and was calculated using the following equation:

$$\text{Evenness} = -\sum [P_i \times \ln(P_i)]/\ln(S) \qquad [1]$$

where P_i is the proportion of each weed species' biomass or density relative to the subplot total, and *S* is species richness of the subplot. Evenness ranges from near 0 (one species highly dominant) to 1 (all species equally abundant).

Weed density, biomass, richness, and evenness were analyzed using mixed-model ANOVA. Fixed effects were year, system, and their interaction. Two random effects (block and system within block) were included in the model. Residuals were visually checked for homogeneity of variance. Weed density and biomass were $\ln(x + 1)$ transformed to correct heteroscedasticity; back-transformed least-squares means are reported. Least-squares means were grouped at significant ($P < 0.05$) factor levels using the Tukey method. All ANOVAs were performed in R v. 3.2.0 (R Foundation for Statistical Computing, Vienna, Austria; R Development Core Team 2018).

Effects of cropping system on weed community composition under AW conditions were analyzed using multivariate techniques in PC-ORD v. 6.08 (MjM Software, Gleneden Beach, OR, USA). We compared weed communities in the AW treatment between cropping systems using permutation-based multivariate analysis of variance (PERMANOVA) with Bray-Curtis distance measures. Weed species occurring in fewer than two AW subplots were omitted. A two-way factorial design (year by system) was first used to test for overall effects. Statistical significance was estimated using a randomization procedure (5,000 runs). Then, pairwise comparisons at significant factor levels were tested manually using a one-way factorial design. Where necessary due to missing data, we used a repeated stratified random sampling procedure and reported P-values after 500 iterations (Peck 2010).

To evaluate weed community composition and identify dominant species (i.e., those making up 95% of the total biomass), individual weed species were ranked within each system and year. Association of individual weed species with particular cropping systems was tested using indicator species analysis (Dufrêne and Legendre 1997). Indicator values for each species were calculated by multiplying relative abundance by relative frequency within a cropping system. Indicator values range from 0 (not detected) to 100 (exclusive association). Significance of indicator values was estimated using a Monte Carlo procedure (5,000 runs) and considered significant when $P < 0.1$. Data from each year were analyzed separately.

Soybean Performance

Soybean biomass and yield were analyzed using mixed-model ANOVA. WF and AW treatment subplots were analyzed in a single model. Fixed effects were year, system, treatment, and their interactions. Three random effects (block, system within block, and entry point within system within block) were included in the model. The relationship between soybean biomass and soybean yield was tested using correlation analysis. We also used correlation analysis to test for relationships between (1) weed species richness (measured in the AW treatment subplot) and soybean biomass (measured in AW and WF), (2) weed species richness (measured in the AW treatment subplot) and soybean yield (AW and WF), and (3) weed species richness (measured in the AW treatment subplot) and percent biomass loss and percent yield loss in the AW relative to the WF treatment, calculated as (WF − AW)/WF.

Results and Discussion

Monthly mean temperatures during both soybean-growing periods of the experiment (May to October in 2014 and 2015) were within 4 C of the historical average (Figure 1). Precipitation in 2014 was similar to the historical average. In 2015, heavy spring rainfall (Figure 1) and poor drainage at the field site caused ponding in some plots in early June, which resulted in patchy soybean germination and slow early-season growth in all systems.

Weed Abundance in AW Conditions

Analysis of weed density data showed a year effect and a system effect, but no year by system interaction (Table 3). Weed density was 56% greater in 2015 compared with 2014. The wet conditions in early June 2015 prevented tine harrowing and delayed the first interrow cultivation until 3 wk after planting (Table 2). Thus, once interrow cultivation was finally possible, weeds were larger than the ideal size for control, and the operation was less effective, a problem that has been discussed in previous literature (Gunsolus 1990). Previous research has shown that propane flame weeding can be more effective than rotary hoeing under wet conditions, and thus could be a potential solution to the problems encountered in 2015, when early-season control practices were compromised (Taylor et al. 2012).

When pooled over years, mean weed density ranged from 28 to 82 stems m^{-2} and was lower in the EWM system compared with

Table 3. Results of ANOVA on weed density, biomass, species richness, and species evenness under ambient weed conditions.[a]

				Species evenness	
	Weed density[a]	Weed biomass	Species richness	By density	By biomass
	stems m^{-2}	g m^{-2}	species 0.5 m^{-2}		
Year[c]					
2014	41 b	26	6.7	0.81	0.57
2015	64 a	26	7.1	0.73	0.50
System[c]					
HF	40 ab	35	6.0 b	0.84	0.59
LF	82 a	25	6.9 b	0.70	0.54
EWM	28 b	14	4.0 b	0.71	0.48
RT	75 a	36	10.9 a	0.84	0.55
Year × system[d]					
2014					
HF	26	34	6.2 AB	0.91	0.67
LF	56	13	6.0 AB	0.73	0.54
EWM	28	16	5.0 B	0.82	0.59
RT	69	69	9.8 A	0.79	0.50
2015					
HF	61	35	5.9 bc	0.77	0.52
LF	117	50	7.8 b	0.67	0.53
EWM	28	12	3.0 c	0.60	0.37
RT	82	19	12.0 a	0.88	0.59
P-value					
Year	0.022	0.909	0.386	0.119	0.422
System	0.003	0.233	<0.001	0.204	0.801
Year × system	0.193	0.079	0.044	0.184	0.517

[a] Systems and years: EWM, enhanced weed management; HF, high fertility; LF, low fertility; RT, reduced tillage. 2014, entry point A; 2015, entry point B.

[b] For density and biomass, ANOVA was performed on $\ln(x + 1)$ transformed values, and back-transformed least-squares means are reported.

[c] Similar letters within a column indicate no significant difference ($P > 0.05$).

[d] Similar letters within a year (uppercase in 2014 and lowercase in 2015) indicate no significant difference between systems.

Table 4. Results of PERMANOVA on weed community using weed density and weed biomass under ambient weed conditions.[a]

	Weed density		Weed biomass
		P	
Year	<0.001		<0.001
System	<0.001		0.002
Year × system	0.014		0.089
	2014	2015	Years combined
		P	
HF vs. LF	0.125	0.100	0.059
HF vs. EWM	0.100	0.100	0.011
HF vs. RT	0.152	0.100	0.063
LF vs. EWM	0.454	0.029	0.589
LF vs. RT	0.033	0.028	0.015
EWM vs. RT	0.029	0.026	0.002

[a] Systems and years: EWM, enhanced weed management; HF, high fertility; LF, low fertility; RT, reduced tillage. 2014, entry point A; 2015, entry point B.

the LF and RT systems (Table 3). Results indicate that the additional cultivation operations in EWM were effective at reducing weed density. Weed densities in our experiment were greater than weed densities found in organic soybean in Iowa (Delate and Cambardella 2004) but lower than weed densities found in organic soybean in Pennsylvania (Ryan et al 2010a).

Average weed biomass ranged from 12 to 69 g m^{-2} across systems and years (Table 3). Weed biomass in all systems was low compared with that reported in previous years in the OCS (Caldwell et al. 2014) and in other long-term organic grain experiments (Davis et al. 2005; Menalled et al. 2001; Ryan et al. 2009b). Contrary to our first hypothesis, no differences in weed biomass between cropping systems were observed (Table 3). In previous years in the OCS, weed biomass varied by cropping system. For example, in 2008, weed biomass was greater in the RT system than the other systems, and in 2009, weed biomass was greater in the HF system than the other systems (Caldwell et al. 2014). During our experiment in 2014 to 2015, weed density and biomass were not different in the HF system compared with the other systems, despite a history of greater poultry manure compost inputs in the HF system. In contrast, Caldwell et al. (2014) reported almost double the weed biomass in the HF compared with the LF system during the first 6 yr of the experiment. In other research, weed abundance has been shown to increase with nutrient additions, especially when nutrients are supplied in excess of crop demand (Blackshaw et al. 2003; Davis and Liebman 2001). Lower than expected weed biomass in the HF and RT systems was likely due to the crop rotation changes in 2011 (i.e., replacing corn with winter barley and buckwheat in the crop rotation of those systems).

Weed Community Composition in AW Conditions

Analysis of weed species richness data showed a year by system interaction (Table 3). In both years, weed species richness was greater in RT than in EWM (Table 3). This result suggests that tillage and cultivation are strong weed community assembly filters. Differences between systems appeared to be intensified by greater spring rainfall resulting in less-effective mechanical weed control in 2015. For example, in 2014, average weed species richness in HF and LF was not different than in RT or EWM, whereas in 2015, weed species richness was lower in HF and LF than in RT and was greater in LF than in EWM (Table 3). Our results are congruent with previous research in conventional production showing that tillage has a large effect on weed species richness and that reduced tillage promotes greater weed species richness (Sosnoskie et al. 2006). In contrast to weed species richness, weed species evenness was not affected by cropping system, meaning that weed communities in all cropping systems were similarly homogenous (Table 3).

PERMANOVA on weed density data indicated that weed community structure differed at the year by cropping system interaction level (Table 4). Weed community composition in RT differed from LF and EWM in both years, and LF differed from EWM in 2015. PERMANOVA on weed biomass data indicated that weed communities differed by year and by system, but not at the interaction level (Table 4). The weed community in RT differed from LF and EWM across years, and HF differed from EWM across years. Differences in weed community structure between years might have been due to efficacy of in-season weed management based on weather conditions, legacy effects of crop rotation entry point, or spatial heterogeneity of the field site.

To elucidate weed community differences identified by PERMANOVA, we ranked the weed species present in each cropping system and year based on their abundance. The number of dominant weed species (i.e., those making up 95% total biomass) ranged from two to eight and was lowest in EWM in both years, reflecting lower weed species diversity compared with other systems (Table 5). Two summer annual species, common ragweed

Table 5. Rank abundance of dominant weed species (i.e., species accounting for 95% of total weed biomass) in each cropping system under ambient weed conditions, with percentages and absolute values of weed density (D, stems m^{-2}) and biomass (B, g m^{-2}) presented.[a]

	2014					2015				
System	Species[b]	%D	D	%B	B	Species[b]	%D	D	%B	B
HF	*Fagopyrum esculentum*	3	1	41	19	*Ambrosia artemisiifolia*	42	27	62	35
	*Sonchus arvensis**	20	5	19	9	*Sonchus arvensis**	18	12	15	8
	Ambrosia artemisiifolia	25	7	11	5	*Sinapis arvensis*	8	5	12	7
	*Taraxacum officinale**	5	1	10	5	*Cirsium arvense**	7	5	3	2
	Sinapis arvensis	5	1	8	4	*Setaria faberi*	5	3	3	1
	*Solanum carolinense**	3	1	4	2					
	Setaria faberi	3	1	4	2					
LF	*Sonchus arvensis**	10	7	56	9	*Ambrosia artemisiifolia*	14	17	31	19
	Setaria faberi	42	31	26	4	*Calystegia sepium**	52	63	31	19
	*Calystegia sepium**	9	7	6	1	*Setaria faberi*	17	21	27	16
	Ambrosia artemisiifolia	9	7	5	1	*Polygonum persicaria*	6	6	7	4
	Setaria glauca	21	16	4	1					
EWM	*Setaria faberi*	49	15	39	7	*Calystegia sepium**	76	23	84	12
	Ambrosia artemisiifolia	10	3	26	5	*Ambrosia artemisiifolia*	15	5	14	2
	Sinapis arvensis	7	2	21	4					
	*Calystegia sepium**	21	7	11	2					
RT	*Fagopyrum esculentum*	3	2	42	47	*Ambrosia artemisiifolia*	11	10	30	13
	Setaria faberi	18	13	23	26	*Cirsium arvense**	19	17	20	9
	*Cirsium arvense**	3	2	15	17	*Setaria glauca*	14	12	17	8
	Chenopodium album	21	15	8	8	*Solanum carolinense**	5	5	13	6
	Amaranthus spp.	1	1	6	7	*Setaria faberi*	6	6	9	4
	Sinapis arvensis	3	2	3	3	*Rumex crispus**	1	1	2	1
						*Calystegia sepium**	4	4	2	1
						*Cyperus esculentus**	2	2	2	1

[a] Systems and years: EWM, enhanced weed management; HF, high fertility; LF, low fertility; RT, reduced tillage. 2014, entry point A; 2015, entry point B.

[b] Asterisks (*) denote perennial species.

(*Ambrosia artemisiifolia* L.) and *S. faberi*, were present in seven out of eight cropping system by year combinations, and in some cases were highly abundant. Winter barley and buckwheat were planted in the HF and RT systems to reduce weed problems; however, they also became volunteer weeds. For example, in the HF and RT systems in 2014, buckwheat accounted for more than 40% of total weed biomass, but only 3% of weed density.

Perennial weeds were abundant in both years; however, their relative abundance and the occurrence of specific species among systems was not consistent across years. Differences in weed species occurrence between years can be partially attributed to soybeans being grown in different areas (i.e., crop rotation entry point A in 2014 and crop rotation entry point B in 2015). In 2014, perennial weeds comprised 33%, 62%, 11%, and 15% of total weed biomass in the HF, LF, EWM, and RT systems, respectively, and in 2015 they made up 3%, 31%, 84%, and 39% of the weed biomass in these systems (Table 5). Perennial sowthistle (*Sonchus arvensis* L.) was the second most abundant species in the HF system in both years, accounting for 19% and 15% of total weed biomass in 2014 and 2015, respectively. This species was also highly abundant in the LF system in 2014 (56% of total weed biomass). Hedge bindweed [*Calystegia sepium* (L.) R. Br.] accounted for 6% and 31% of total biomass in the LF system and 11% and 84% of total biomass in the EWM system in 2014 and 2015, respectively. Canada thistle [*Cirsium arvense* (L.) Scop.] accounted for 15% and 20% of total weed biomass in the RT system in 2014 and 2015, respectively. Five out of eight dominant weed species in the RT system in 2015 were perennial, providing partial support for our second hypothesis that perennial weed species would dominate the weed community in a cropping system with reduced soil tillage. Our results are congruent with Gruber and Claupein (2009), who found *C. arvense* density, biomass, and seedbank abundance increased with chisel plowing compared with when more intense primary tillage methods were used. However, other perennial species such as *Sonchus arvensis* and *C. sepium* were more abundant in the HF, LF, and EWM systems compared with the RT system (Table 5). The relatively high abundance of perennial weed species in the HF, LF, and EWM systems, despite more intensive tillage, was likely due to the tillage and cultivation practices failing to reduce carbohydrate reserves in roots (*Sonchus arvensis*) and rhizomes (*C. sepium*). In a meta-analysis of perennial weed management in organic cropping systems, Orloff et al. (2018) report that although mechanical weed control was the most commonly researched method, its efficacy was variable, and it did not outperform other methods of control. Differences in sprouting activity and readiness of root and rhizome buds in relation to tillage and cultivation is another potential reason why different perennial species were dominant in different cropping systems (Brandsæter et al. 2010).

Indicator species analysis showed that 11 weed species were associated with cropping systems at the $P < 0.1$ level (Table 6). One species was associated with the EWM system, three were associated with the HF system, and three were associated with the LF system, while eight species were associated with the RT system (counting years separately). This indicates that management practices used in the different cropping systems acted as weed community filters. Twice as many species were observed to be significant indicators of a given system in 2015 compared with 2014. As discussed previously, heavy precipitation in June 2015 reduced the efficacy of mechanical weed management practices and likely contributed to the difference in indicator species across years. Two species, *C. album* and buckwheat, were consistently associated with the RT system in both years. Two other species were inconsistent indicators across years. Specifically, *C. sepium* was associated with the EWM system in 2014 and the LF system in 2015, and *S. faberi* was associated with the

Table 6. Results from indicator species analysis using weed biomass and weed density under ambient weed conditions.[a,b]

	2014					2015				
		Biomass		Density			Biomass		Density	
Species[c]	System	IV	P	IV	P	System	IV	P	IV	P
Ambrosia artemisiifolia	–	–	–	–	–	HF	–	–	46.9	0.038
*Calystegia sepium**	EWM	66.8	0.037	–	–	LF	57.9	0.023	70.6	<0.001
Chenopodium album	RT	93.7	0.006	88.2	0.005	RT	–	–	63	0.061
*Cirsium arvense**	–	–	–	–	–	RT	85.2	0.024	78.5	0.015
Fagopyrum esculentum	RT	–	–	56.2	0.091	RT	75	0.029	75	0.032
Hordeum vulgare	–	–	–	–	–	RT	75	0.03	75	0.029
Poa spp.	–	–	–	–	–	RT	100	0.002	100	0.003
Polygonum persicaria	–	–	–	–	–	LF	62	0.083	54.4	0.072
Setaria faberi	RT	66.6	0.086	–	–	LF	75.6	0.041	70.4	0.028
Sinapis arvensis	–	–	–	–	–	HF	80.4	0.075	–	–
*Taraxacum officinale**	HF	66.7	0.027	66.7	0.03	–	–	–	–	–

[a] Systems and years: EWM, enhanced weed management; HF, high fertility; LF, low fertility; RT, reduced tillage. 2014, entry point A; 2015, entry point B.
[b] Significance of indicator values (IV) was assessed with a Monte Carlo procedure and species with a significant ($P < 0.1$) IV are reported.
[c] Asterisks (*) denote perennial species.

Table 7. Results of ANOVA on soybean biomass and yield under ambient weed and weed-free conditions.[a]

	Soybean biomass	Soybean yield
	———g m^{-2}———	
Year[b]		
2014	498 a	297 a
2015	317 b	183 b
System[b]		
HF	453	258 a
LF	374	239 ab
EWM	366	205 b
RT	436	257 a
Treatment[b]		
Ambient weed	390	229 b
Weed free	424	251 a
Year × system[c]		
2014		
HF	553 A	326
LF	505 A	300
EWM	466 A	252
RT	467 A	310
2015		
HF	353 ab	190
LF	242 b	179
EWM	266 ab	159
RT	405 a	204
P		
Year	<0.001	<0.001
System	0.064	0.011
Treatment	0.234	0.004
Year × system	0.039	0.189
Year × treatment	0.878	0.328
System × treatment	0.266	0.115
Year × system × treatment	0.710	0.803

[a] Systems and years: EWM, enhanced weed management; HF, high fertility; LF, low fertility; RT, reduced tillage. 2014, entry point A; 2015, entry point B.
[b] For each effect, similar letters within a column indicate no significant difference ($P > 0.05$).
[c] For the year × system interaction effect, similar letters within a year (uppercase in 2014 and lowercase in 2015) indicate no significant difference between systems.

RT system in 2014 and the LF system in 2015. In addition to *C. sepium*, other perennial indicator species included dandelion (*Taraxacum officinale* F. H. Wigg.), which was associated with the HF system in 2014, and *C. arvense*, which was associated with the RT system in 2015. The large number of species associated with the RT system is consistent with our observation that this system had both high species richness and a distinct weed community relative to the other systems.

Results from this research are congruent with previous research on the effect of management practices on weed community assembly. Ryan et al. (2010b) analyzed the soil weed seedbank in a long-term cropping systems experiment that compared a standard conventional management system to two organic management systems that differed in nutrient input (manure vs. legume). Indicator species analysis showed that *T. officinale* was associated with the manure-based organic cropping system that had higher nutrient inputs, whereas *S. faberi* was associated with the legume-based organic cropping system that had lower nutrient inputs (Ryan et al. 2010b). Interestingly, *C. album* and *C. arvense*, which were both associated with the RT system in this research, were both associated with the conventional system, which used reduced tillage relative to the legume-based and manure-based organic cropping systems (Ryan et al. 2010b).

Soybean Performance

Average soybean population, measured in August after weed management practices occurred, did not differ by cropping system ($P > 0.05$) and was 473,800 plants ha^{-1} in 2014 and 517,900 plants ha^{-1} in 2015, representing 74% and 72% of seeding rates, respectively. We observed a year by system interaction effect on soybean biomass, but no differences based on weed management treatment (Table 7). Soybean biomass was not affected by cropping system in 2014. In 2015, soybean biomass was lower in LF than in RT, whereas soybean biomass in HF and EWM did not differ from LF or RT.

We observed effects of year, system, and weed management treatment on soybean yield, but no interactions between these factors (Table 7). Although the results from the analysis of soybean yield varied slightly from the soybean biomass results, soybean yield and soybean biomass were correlated ($r = 0.70$, $P < 0.001$). Compared with historical soybean yields in the OCS trial (2005 to 2010), yields in our experiment were average to above average in 2014, but below average in 2015 (Caldwell et al. 2014). Lower yields in 2015 appeared to be caused by high precipitation in June 2015 and poor drainage at the field site limiting soybean germination and early growth. Low precipitation in August 2015 may have limited later growth and pod fill (Figure 1). Across both years, EWM had lower soybean yields than HF and RT ($P < 0.05$), whereas LF yields were intermediate. Thus, we did not find support for our third hypothesis that soybean yield would be greatest in a cropping system with

Table 8. Pearson correlations between weed species richness (species 0.5 m^{-2}) in the ambient weed (AW) treatment, soybean biomass and yield (g m^{-2}) in AW and weed-free (WF) treatments, and percent biomass and yield loss in the AW relative to the WF treatment.

	Soybean biomass			Soybean yield		
Weed species richness (AW)	AW	WF	% Loss	AW	WF	% Loss
	r					
2014	0.02	0.04	0.01	0.29	0.50 *	0.32
2015	0.30	0.26	−0.12	0.31	0.75 **	0.41

*P < 0.1.
**P < 0.01.

additional soil tillage and cultivation compared with systems with fewer weed management operations. Soybeans in the EWM system lagged behind the HF and RT systems in vegetative growth stage during both growing seasons (Ball 2017).

Low soybean yields in the EWM system were unexpected, considering that during the first 6 yr of the OCS experiment (2005 to 2010), soybean yields in EWM were among the highest (Caldwell et al. 2014). There are several possible explanations for low yields in EWM. Extra interrow cultivation in late July (Table 2) could have damaged soybean roots and depleted soil moisture during late-summer pod fill. Early false-seedbed tillage and other extra tillage in EWM in previous years might have damaged soil structure and depleted soil organic matter. Furthermore, the LF and EWM systems have a history of lower nutrient inputs compared with the HF and RT systems, and soil nutrient depletion may also have limited yield potential.

Soybean biomass did not differ between the AW and WF treatments (Table 7). However, soybean grain yield was 10% greater in the WF treatment compared with the AW treatment (Table 7). The lack of a treatment effect on soybean biomass could be due to the fact that biomass samples were collected earlier than grain yields, which may have been before the onset of weed competition effects. The RT system in our experiment had the highest weed density and species richness, greatest number of indicator weed species, and a weed community that was distinct from both the LF and EWM systems. Despite this, soybean yields in the RT system were among the highest in our experiment, suggesting that high weed abundance and diversity is not necessarily associated with low yield.

Our WF treatment allowed us to examine the soybean production potential of the soil in each cropping system in the absence of weed competition. No relationship was found between weed species richness in AW subplots and soybean biomass in either the AW or WF treatments in either year (Table 8). However, we found a positive relationship between soybean yield measured in WF subplots and weed species richness measured in adjacent AW subplots in both years (Table 8). This suggests that management factors that promoted weed community diversity, such as reduced tillage, may have also increased yield potential of the soil. It is also plausible that diverse weed inputs in years past may have contributed positively to soil quality and yield potential. However, the relationship between weed species richness and soybean yield measured in the AW subplots was not significant, suggesting that weed competition prevented the higher yield potential from being realized. Our results echo those of Ryan et al. (2010a), who found higher yield potential, but similar actual yields, in long-term organic versus conventional systems. We also tested for relationships between weed species richness in the AW subplots and percent soybean biomass and yield loss using data from both the AW and WF subplots (sensu Storkey and Neve 2018); however, these relationships were not significant (Table 8).

Results from our research suggest that crop and soil management that led to higher weed species richness in the past might have increased the soybean yield potential relative to management practices that led to lower weed species richness. Greater weed species diversity could increase the diversity of plant residue inputs to the soil and thus increase soil resource pool diversity and overall capacity of the soil to support plant growth (Smith et al. 2010, 2011). Alternatively, past management practices that reduced weed species richness might have also decreased the yield potential of the soil. In other words, the more frequent interrow cultivation in the EWM system that resulted in lower weed populations and weed community diversity might have degraded soils and lowered the capacity of the soil to support soybean growth. It is also possible that shorter-term effects such as root pruning, soil moisture depletion, and soil compaction from late summer cultivation might account for these results.

The purpose of this research was to evaluate weed communities and their effects on soybean performance in a long-term organic cropping systems experiment. In our 2-yr nested experiment, we observed differences in weed density, weed species richness, and weed community composition among cropping systems primarily related to differences in tillage intensity, rather than nutrient inputs, across the four cropping systems that were tested. Overall, soybean yields were 10% greater in the WF subplots compared with the AW subplots. Although hand weeding used in the WF subplots may not be practical in large-scale organic grain crop production, our results suggest that investing in improved practices that reduce weed competition might be profitable given price premiums for organic crops. Counterintuitively, soybean yields were lowest in the EWM system, where additional tillage and cultivation resulted in relatively low weed abundance and diversity. This suggests that intensive mechanical weed control, though effective in reducing weed abundance and diversity, might also reduce soybean yield potential. Future research should aim to increase crop yield in organic production systems by gaining insights into how weed management practices influence not only weed density and weed community structure, but also soil organic matter, soil nutrient reserves, soil moisture, soil hardness, crop rooting depth, and other factors that influence crop yield potential.

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