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Weed Community Composition in Simple and More Diverse Cropping Systems

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Weed communities in three cropping systems suitable for the Midwestern USA were studied from 2017 to 2020 to examine how crop diversification and the intensity of herbicide use affected weed community diversity, stand density, and aboveground mass. A baseline 2-year cropping system with corn (*Zea mays* L.) and soybean (*Glycine max* (L.) Merr.) grown in alternate years was diversified with cool-season crops, namely oat (*Avena sativa* L.), red clover (*Trifolium pratense* L.), and alfalfa (*Medicago sativa* L.) in 3-and 4-year systems. Herbicide was not applied in the cool-season crops. Changing weed management regime from broadcast to banded application and interrow cultivation in corn and omitting herbicide in cool-season crops of the 3- and 4-year rotations resulted in an overall reduction of herbicide a.i mass. The reduction in the mass of herbicide active ingredients was associated with increases in weed stand density, aboveground mass, and community diversity. Increased weed abundance under herbicide mass reduction was not associated with crop yield loss. In the cool-season crops phases of the 3- and 4-year rotations, weed emergence was increased but weed growth was not, as compared with the warm-season crop environments. The dominance of aggressive weed species such as common waterhemp (*Amaranthus tuberculatus* (Moq ex DC) J.D. Sauer) and common lambsquarter (*Chenopodium album* L.) tended to be greater in corn and soybean phases of the rotations than in oat, red clover, and alfalfa.

Keywords: weed community composition, diversity, evenness, richness, Midwestern-United States, agroecology, integrated weed management

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INTRODUCTION

The composition of weed communities found in agricultural fields is strongly affected by the types of crops grown and their attendant management practices (Mohler, 2001; Légère et al., 2005; Culpepper, 2006; Smith and Gross, 2007). The US Corn Belt is dominated by monocultures and short-term rotations of corn and soybean (Center for Spatial Information Science and Systems, 2021). In response to simplified crop management customized for corn and soybean, weed communities have shifted to domination by aggressive summer annual species including common waterhemp (*Amaranthus tuberculatus* (Moq ex DC) JD Sauer), Palmer amaranth (*Amaranthus palmeri* S. Wats), giant ragweed (*Ambrosia trifida* L.), common lambsquarter (*Chenopodium album* L.), and wooly cupgrass (*Eriochloa villosa* (Thunb) Kunth) (Owen, 2008; Kruger et al., 2009; Reddy and Norsworthy, 2010). Improved understanding of how management practices influence weed community composition could inform weed managers whether crop losses to weed competition are likely to occur and whether a weed community is shifting toward dominance by species that are more aggressive toward crops (Liebman, 2001).

Cropping system diversification strategies that are designed to reduce reliance on external inputs, including herbicides, can balance productivity, profitability, and environmental quality goals (Davis et al., 2012; Hunt et al., 2017, 2019, 2020; Bowles et al., 2020; Tamburini et al., 2020; Beillouin et al., 2021). They can also increase cropping systems' overall resilience to growing environmental adversity (Bowles et al., 2020) and can be effective in suppressing weeds (Weisberger et al., 2019). Increased crop species richness within crop sequences coupled with diversification of management practices applied to maximize crop and minimize weed resource acquisition, are expected to challenge weeds with large sets of stress and mortality factors compared to simple cropping systems (Liebman and Gallandt, 1997; Liebman and Staver, 2001; Westerman et al., 2005).

Storkey and Neve (2018) hypothesized that a more diverse weed community can be less competitive toward crops and weed seedbank diversity can be used as an indicator of cropping system sustainability. Nonetheless, few studies have examined weed community composition in rotations with crop species other than corn (*Zea mays* L.), soybean (*Glycine max* (L.) Merr.), and wheat (*Triticum aestivum* L.), especially in fully phased settings, in which all crop phases within a rotation are present each year to control for year to year variations in weather conditions and management efficacy (Payne, 2015). Davis et al. (2005b) studied weed aboveground and underground community shifts in four row-crop systems under four combinations of weed management and tillage regimes and found a strong negative relationship between crop yield and weed diversity, density, and total biomass; individual responses of only common waterhemp and common lambsquarter were reported. Smith and Gross (2007) compared a monoculture of corn with 2- and 3-year rotations of corn with soybean and winter wheat, with or without cover crops and found that crop rotation and diversity had weak effects on weed community composition, whereas the cover crop in a particular rotation played an important role in weed species diversity. Increased reliance on glyphosate-based weed management has caused weed floras to shift to dominance by hard-to-control species (Owen, 2008), but it is unclear whether reduction in herbicide use would cause the same problem. Liebman et al. (2021) provided empirical evidence to support the hypothesis that seedbank diversity could be used as an indicator of cropping system sustainability (Storkey and Neve, 2018).

This study was pursued to address the current gap of information concerning weed community density and aboveground mass responses to the filtering effects of different crop and weed management programs (Ryan et al., 2010; Fried et al., 2012). We studied three different cropping systems suitable for the US Corn Belt. The baseline system was a conventional corn—soybean system. We diversified that baseline system with oat (*Avena sativa* L.), red clover (*Trifolium pratense* L.), and alfalfa (*Medicago sativa* L.). Conventional broadcast herbicide and reduced herbicide management regimes were applied in a split-plot manner to corn phases of the three rotations. We hypothesized that diversified cropping systems, with reduced use of chemical herbicides, would provide weed control equal in effectiveness to the conventional approaches applied in the 2-year corn and soybean system. We assessed weed control efficacy by measuring weed aboveground mass and population densities. Additionally, we measured crop yields, positing that differences in weed aboveground mass and density could be reflected in differences in crop yields. Next, we hypothesized that the weed communities in the more diverse cropping systems would be more diverse, more even, and more species-rich than those in the 2-year corn and soybean system, reflecting a broader range of crop species and their attendant management practices in the more diverse rotations. Finally, we hypothesized that including oat, red clover, and alfalfa in rotations with corn and soybean would reduce the density and aboveground mass of noxious weed species in corn and soybean when the rotations cycles returned to corn and soybean.

MATERIALS AND METHODS

Empirical measurements of weed community composition were made from 2017 to 2020 at Iowa State University's Marsden Farm in Boone County, Iowa, USA, (42° 01'N, 93° 47'W, 333 m above sea level). All soil types present at the site are Mollisols (Chen et al., 2014). A detailed description of the experiment site and crop management can be found in Liebman et al. (2021) and the field layout and experiment design are provided in Nguyen and Liebman (accepted). Briefly, a randomized complete block, split-plot design with four replications was used to study three different crop rotation systems (2-, 3-, or 4-year; the crop sequence in each rotation was presented in Table 1 of Nguyen and Liebman, accepted). The main-plot factor, i.e., the crop identity, was represented by crop species and the rotation system in which it occurred (C2-corn in the 2-year rotation, C3-corn in the 3-year rotation, C4-corn in the 4-year rotation, S2-soybean in the 2-year rotation, S3-soybean in the 3-year rotation, S4-soybean in the 4-year rotation, O3 - oat in the 3-year rotation, and O4- oat in the 4-year rotation, and A4-alfalfa in the 4-year rotation). The split-plot factor, i.e., the weed management regime applied in the corn phase (corn weed management), was represented by herbicide level (conventional—pre- and post-emergent herbicides broadcast over the whole corn area, or low—post-emergence herbicides banded 38 cm wide on top of corn rows). The reduction of herbicide mass in the low herbicide treatment was supplemented by interrow cultivation. Details concerning crop genotypes and weed management regimes are provided in **Table 1**.

Volunteer crops from a preceding crop season, such as a volunteer corn plant in a soybean plot or a soybean plant in an oat plot, were not considered weeds. Data were collected for individual weed species aboveground mass and density, community weed biomass and density, and crop yield. Weeds were surveyed 4–6 weeks before corn and soybean harvests, and 2–3 weeks after oat harvest or the last hay cut of the season. The passage of a few weeks between oat and alfalfa harvest and weed surveys allowed physically damaged plants in those crops to grow back to recognizability. Weed aboveground samples were

TABLE 1 | Crop variety or hybrid and management from 2017 to 2020 field seasons.

Year	Activity or input	Low herbicide	Conventional herbicide	Low herbicide	Conventional herbicide
		Corn	**Corn**	**Soybean**	**Soybean**
2017	Hybrid or variety	Epley E1420	Epley E1420	Latham L2758 R2	Latham L2758 R2
	Planting date	9-May	9-May	16-May	
	Interrow cultivation date	Jun. 7	Jun. 7	none	none
	Harvest date	Oct. 19	Oct. 19	Oct. 19	
	Herbicides applied (kg ai./ha)	POST: tembotrione (0.049) applied May 31, interrow cultivated Jun. 7	PRE: thiencarbazone methyl (0.037), isoxaflutole (0.093)	PRE: flumioxazin (0.109); POST: glyphosate as potassium salt (1.249), acifluorfen (0.224)	PRE: flumioxazin (0.109); POST: glyphosate as potassium salt (1.249), acifluorfen (0.224)
	Total (kg a.i./ha)	0.049	0.13	1.581	1.581
	Weed sampling date	Sep. 5 and 6	Sep. 5 and 6	Sep. 6, 7, and 8	Sep. 6, 7, and 8
2018	Hybrid or variety	Epley E1420	Epley E1420	Latham L2758 R2	Latham L2758 R2
	Planting date	8-May	8-May	Jun. 3	Jun. 3
	Interrow cultivation date	Jun. 4	none	none	none
	Harvest date	Oct. 30	Oct. 30	Oct. 29	Oct. 29
	Herbicides applied (kg ai./ha)	POST: tembotrione (0.054)	PRE: thiencarbazone methyl (0.037), isoxaflutole (0.092); POST: mesotrione (0.105), nicosulfuron (0.053)	PRE: flumioxazin (0.096); POST: glyphosate as potassium salt (1.540), lactofen (0.140)	PRE: flumioxazin (0.096); POST: glyphosate as potassium salt (1.540), lactofen (0.140)
	Total (kg a.i./ha)	0.054	0.287	1.776	1.776
	Weed sampling date	Sep. 11, 12, and 13	Sep. 11, 12, and 13	Sep. 17, 19, 20, and 21	Sep. 17, 19, 20, and 21
2019	Hybrid or variety	Epley E1730	Epley E1730	Latham 2684 L (Liberty Link)	Latham 2684 L (Liberty Link)
	Planting date	Jun. 3	Jun. 3	Jun. 10	Jun. 10
	Interrow cultivation date	none, due to weather adversity	none	none	none
	Herbicides applied (kg ai./ha)	POST: tembotrione (0.049)	PRE: thiencarbazone methyl (0.037), isoxaflutole (0.092); POST: mesotrione (0.105), nicosulfuron (0.053)	PRE: flumioxazin (0.096); POST: glufosinate ammonium (0.594), clethodim (0.136)	PRE: flumioxazin (0.096); POST: glufosinate ammonium (0.594), clethodim (0.136)
	Total (kg a.i./ha)	0.049	0.287	0.826	0.826
	Weed sampling date	Sep. 17 and 18	Sep. 17 and 18	Sep. 30	Sep. 30
2020	Hybrid or variety	Epley E1730	Epley E1730	Latham 2684 L (Liberty Link)	Latham 2684 L (Liberty Link)
	Planting date	Apr. 23	Apr. 23	13-May	13-May
	Interrow cultivation date	Jun. 8	none	none	none
	Harvest date	Oct. 2	Oct. 2	Sep. 23	Sep. 23
	Harvest date	Nov. 6	Nov. 6	Oct. 18	Oct. 18
	Herbicides applied (kg ai./ha)	POST: tembotrione (0.051)	PRE: thiencarbazone methyl (0.037), isoxaflutole (0.092); POST: mesotrione (0.105), nicosulfuron (0.053)	PRE: flumioxazin (0.096); POST: glufosinate ammonium (0.594), clethodim (0.136)	PRE: flumioxazin (0.096); POST: glufosinate ammonium (0.594), clethodim (0.136)
	Total (kg a.i./ha)	0.051	0.287	0.826	0.826

(Continued)

TABLE 1 | Continued

Year	Activity or input	Low herbicide	Conventional herbicide	Low herbicide	Conventional herbicide
	Weed sampling date	Sep. 14 and 15	Sep. 14 and 15	Sep. 16	Sep. 16
		Oat	**Oat**	**Alfalfa**	**Alfalfa**
2017	Hybrid or variety	IN09201	IN09201	Leafguard	Leafguard
	Planting date	Apr. 12	Apr. 12	Mar. 29, 2016	Mar. 29, 2016
	Stubble clipping	Aug. 7 in O3 and O4 and Sep. 11 in O4	Aug. 7 in O3 and O4 and Sep. 11 in O4	Aug. 10, 2016	Aug. 10, 2016
	Harvest date	Jul. 17	Jul. 17	Jun. 6, Jul. 7, Aug. 7, and Sep. 11	Jun. 6, Jul. 7, Aug. 7, and Sep. 11
	Weed sampling date	Sep. 25, 27, 28, and 29	Sep. 25, 27, 28, and 29	Sep. 25, 27, 28, and 29	Sep. 25, 27, 28, and 29
2018	Hybrid or variety	IN09201	IN09201	Leafguard	Leafguard
	Planting date	Apr. 24	Apr. 24	Apr. 12, 2017	Apr. 12, 2017
	Stubble clipping	Sep. 11	Sep. 11	Sep. 11, 2017	Sep. 11, 2017
	Harvest date	Jul. 20	Jul. 20	Jun. 4, Jul. 9, and Sep. 10	Jun. 4, Jul. 9, and Sep. 10
	Weed sampling date	Sep. 26, Oct. 4, 15, 16, 18, and 19	Sep. 26, Oct. 4, 15, 16, 18, and 19	Sep. 26, Oct. 4, 15, 16, 18, and 19	Sep. 26, Oct. 4, 15, 16, 18, and 19
2019	Hybrid or variety	IN09201	IN09201	Leafguard	Leafguard
	Planting date	Apr. 16	Apr. 16	Apr. 24, 2018	Apr. 24, 2018
	Stubble clipping	none	none	none	none
	Harvest date	Jul. 24 and 29	Sep. 24 and 29	Jun. 7, Jul. 12, Aug. 26, 2019	Jun. 7, Jul. 12, Aug. 26, 2019
	Weed sampling date	Sep. 23, 24, 25, and 26, Oct. 3, 4, 7, and 8	Sep. 23, 24, 25, and 26, Oct. 3, 4, 7, and 8	Sep. 23, 24, 25, and 26, Oct. 3, 4, 7, and 8	Sep. 23, 24, 25, and 26, Oct. 3, 4, 7, and 8
2020	Hybrid or variety	IN09201	IN09201	Leafguard	Leafguard
	Planting date	Apr. 2, May 7*	Apr. 2, May 7*	Apr. 16, 2019	Apr. 16, 2019
	Stubble clipping	none	none	none	none
	Harvest date	Jul. 24	Jul. 24	Jun. 2, Jul. 6, and Aug. 17	Jun. 2, Jul. 6, and Aug. 17
	Weed sampling date	Sep. 23, 24, and 29, Oct. 2, 6, 7, and 8	Sep. 23, 24, and 29, Oct. 2, 6, 7, and 8	Sep. 23, 24, and 29, Oct. 2, 6, 7, and 8	Sep. 23, 24, and 29, Oct. 2, 6, 7, and 8

Corn was planted at 12,950 seeds/ha, soybean at 56,656 seeds/ha, oat at 80.7 kg/ha, red clover and alfalfa at 19.1 kg/ha. PRE and POST herbicide in corn and soybean refers to pre-emergence and post-emergence, relative to weed emergence. No herbicide was applied in oat, red clover, and alfalfa. "Belle" (in 2017) or "Mammoth" (in 2018–2020) red clover was intercropped with oat in the 3-year rotation (O3). Alfalfa was intercropped with the oat phase in the 4-year rotation (O4) and was overwintered to the following year as a sole crop (A4).

* *Oat was replanted in 2020 due to poor germination.*

collected from eight quadrats arranged in a 4 x 2 grid throughout each experimental unit (eu). The sample grid was randomized every year in such a way that quadrats were at least 3 m away from plot borders to avoid any edge effect.

Individual Weed Species Abundance

All the same-species plants from each eu were clipped, enumerated, dried, and weighed at ~0% moisture together to make single data points per eu. The total surveyed area was 18.5 m^2/eu (8 x 2.3 m^2) in corn and soybean and 2.2 m^2/eu (8 x 0.28m^2) in oat and alfalfa. Plants were identified to species as guided by Uva et al. (1997). Plant counts and dried weights were converted to plants m^{-2} and g m^{-2}.

Weed Community Abundance

Weights and counts of individual weed species from each eu were tallied for community abundance.

Ecological Indices

Weed community diversity is the combination of two indices. The community evenness index ranges from 0 to 1, with higher values indicating higher evenness (Alatalo, 1981). The species richness index is a count of the number of species observed. The presence of rare species in low abundance decreases the overall evenness of a weed community (Pielou, 1984; Stirling and Wilsey, 2001). Studying all three indices, i.e., diversity, evenness, and richness, generates a more complete description of a community than any one of the indices (Morris et al., 2014). Simpson's diversity, evenness, and richness indices were calculated in terms of stand density and aboveground mass in each eu. We evaluated eighteen weed communities, corresponding to nine crop identities crossed with two weed management regimes in corn.

Let:

S represent species richness (i.e., the number of species presented),
n_i represent density of the i*th* species (plants m^{-2}),
N represent density of all presented species (plants m^{-2}),
b_i represent aboveground mass of the i*th* species (g m^{-2}),
B represent aboveground mass of all species, g m^{-2}, and
p_{i_d} and p_{i_b} represent the proportional of density or aboveground biomass of the i*th* species.

Community diversity was evaluated with Simpson's index, $Simpson's\ D=\frac{1}{D}=\frac{1}{\sum p_i^2}$, because it is less sensitive to sample size and is useful to describe evenness (Nkoa et al., 2015). Simpson's evenness index was calculated with $\frac{\frac{1}{D}}{S}$. The p_i component in Simpson's diversity and evenness indices here was calculated with stand count ($\frac{n_i}{N}$) or biomass ($\frac{b_i}{B}$). Ideally, only one richness index is needed because it is the number of species presented. However, two ABUTH (*Abutilon theophrasti*) plants that were found in 2019 were too light to register on a scientific scale, resulting in zero weight for the species' aboveground mass. Therefore, the richness index was calculated for both stand and aboveground mass. The evenness index was thus calculated with the relevant richness index with regards to stand count and aboveground mass.

Crop Yields

Six 84-m long rows of corn and soybean (383 m^2) were harvested from each eu, whereas for oat and alfalfa, whole plots were harvested (i.e., two adjacent subplots combined, 1,530 m^2). Yields were adjusted to moisture concentrations of 155 g H_2O kg^{-1} for corn, 130 g H_2O kg^{-1} for soybean, 140 H_2O kg^{-1} for oat grain, and 150 g H_2O kg^{-1} for alfalfa.

Model Fitting

Block, crop identity, weed management regime applied to the corn phase of a rotation (corn weed management), and the interaction of crop identity and corn weed management were considered fixed factors; year and the interaction between year and the fixed factors were considered random factors; and the residual was random by default. Block was treated as a fixed factor to control for the different field conditions across sections and reduce the variance between eu's (Dixon, 2016).

R version 4.1.2 (R Development Core Team, 2021) was used for all data organization, manipulation, analysis, models diagnosis, and result presentation. Statistical tests were evaluated at an $\alpha = 0.05$ level of significance. All the response variables were natural logarithm (ln) transformed to ensure homogeneity of variance. For each response, the minimum non-zero value was added to zero values before transformation). Type III sums of squared error were calculated with the `emmeans` package's `joint_tests` function to accommodate unbalanced data with interaction (version 1.7.2, Lenth, 2022). Results were back-transformed for presentation. Degree of freedom adjustment was done with Satterthwaite's method. *P*-values adjustment was done with Tukey's method.

Stand diversity, stand evenness, stand richness, aboveground mass diversity, aboveground mass evenness, aboveground mass richness, community aboveground density, community aboveground mass, individual species density, and individual species aboveground mass were analyzed separately with a linear mixed-effects model, using the `lmer` function in the `lme4` package (version 1.1–27.1, Bates et al., 2015) according to the following model.

$$\begin{aligned} R_{ijklm} &= \mu + B_i + C_j + H_k + CH_{jk} + Y_l + BY_{il} + YC_{lj} \\ &\quad + YH_{lk} + YCH_{ljk} + BYC_{ijl} + \epsilon_{ijkl} \end{aligned} \tag{1}$$

where,

R is one of the aforementioned responses,
μ is the overall mean,
B is the block,
Y is the year,
C is the crop identity,
H is the corn weed management,
CH is the interaction between crop identity and corn weed management,
BY is the block within a year,
YC is the interaction between crop identity and year,
YH is the interaction between year and corn herbicide,

YCH is the interaction between year, crop identity, and corn weed management,
BYC is the interaction between block, year, and crop identity, and
ϵ_{ijkl} is the residual.

The crop identity term in the right-hand side of the model (Equation 1) represents the main-plot effect of the experiment, which comprises of the crop species and the rotation to which it belonged. In this present study, "cropping system" is the combination of "rotation system" (2-, 3-, and 4-year) and herbicide regime in corn (low or conventional); and crop type represents growing condition, so corn and soybean were grouped as warm-season crops, whereas oat and alfalfa were grouped as cool-season crops. With this model, we tested the following three sets of hypotheses for treatment effects on weed community stand diversity, community stand evenness, community stand richness, community aboveground mass diversity, community aboveground mass evenness, community aboveground mass richness, community aboveground density, and community aboveground mass:

1) The response variables increased as cropping system diversity increased.
2) In the same crop species the response variables differed between cropping systems.
3) In the same crop species the response variables differed between different crop types within a given cropping system.

The first set of hypotheses was tested by contrasting the responses in the 2-year rotation with those in the average of the 3- and 4-year rotations and the responses in the 3-year rotation with those in the 4-year rotation. The second set of hypotheses was tested by contrasting the responses in the same crop species within different rotations. The third set of hypotheses was tested by contrasting the average responses in the warm-season crops between rotations, in the cool-season crops between rotations, in the warm-season vs. cool-season crops within the same rotation, and between the warm-season crops and the cool-season crop(s) averaged over rotations.

The same sets of contrasts used to evaluate weed community ecological indices, weed community aboveground mass, and weed community stand density were applied to data concerning the stand density and aboveground mass of the seven most abundant weed species to test for the treatment effects on those species:

4) The response variables differed between rotations for the same crop species, differed between rotations, and differed between crop type within a given cropping system.

The fourth set of hypotheses was tested by contrasting individual weed species density and aboveground mass (a) in the 2-year rotation vs. the average of 3- and 4-year rotations and in the 3- vs. 4-year rotation, (b) in the same crop species or type between rotations, (c) in different crop types within the same rotation, and (d) in different crop types averaged over rotations.

A different set of linear mixed-effects models was used to analyze corn, soybean, and oat yields (`lme4` version 1.1-27.1, Bates et al., 2015):

TABLE 2 | Contrasts of rotation effect (expressed by Crop ID) on crop yields.

	ANOVA				Comparison		
Source of variation	**df1**	**df2**	***F***	***p***	**Contrast**	**Ratio**	***p***
(A) Corn							
Crop ID	2	6	3.19	0.1138	C2 vs. C3	0.94	0.1882
Corn weed management	1	3	0.32	0.6088	C2 vs. C4	0.93	0.1278
Crop ID x Corn weed management	2	6	2.20	0.1914	C3 vs. C4	0.99	0.9507
(B) Soybean							
Crop ID	2	6	8.22	0.0191	S2 vs. S3	0.96	0.5499
Corn weed management	1	3	0.18	0.7018	S2 vs. S4	0.86	0.0181
Crop ID x Corn weed management	2	6	0.62	0.5677	S3 vs. S4	0.90	0.0670
(C) Oat							
Crop ID	1	2	1.14	0.3979	O3 vs. O4	0.91	0.3979

The abbreviations on the contrast column are crop identities, which are the combinations of the first letter in crop species names and the rotation in which it occurred. Corn weed management: low herbicide or conventional. Crop ID: crop species and the cropping system in which it occurred: C2, corn in the 2-year rotation; C3, corn in the 3-year rotation; C4, corn in the 4-year rotation; S2, soybean in the 2-year rotation; S3, soybean in the 3-year rotation; S4, soybean in the 4-year rotation; O3, oat in the 3-year rotation; O4, oat in the 4-year rotation.

$$R_{ijkm} = \mu + B_i + C_j + H_k + CH_{jk} + Y_l + BY_{il} + YC_{lj} + YH_{lk} + YRH_{lij} + BYC_{ilj} + \epsilon_{ijkl} \quad (2)$$

where,
R is the individual crop yield, and
all the terms in the right-hand side of the model are as defined in Equation (1).

$$R_{ijl} = \mu + B_i + C_j + Y_l + BY_{il} + YC_{lj} + \epsilon_{ijl} \quad (3)$$

where,
R is oat yield,
μ is the overall mean,
B is the block,
Y is the year,
C is the crop identity,
BY is the block within a year,
YC is the interaction between crop identity and year,
ϵ_{il} is the residual.

$$R_{il} = \mu + B_i + Y_l + \epsilon_{il} \quad (4)$$

where,
R is alfalfa yield,
μ is the overall mean,
B is the block,

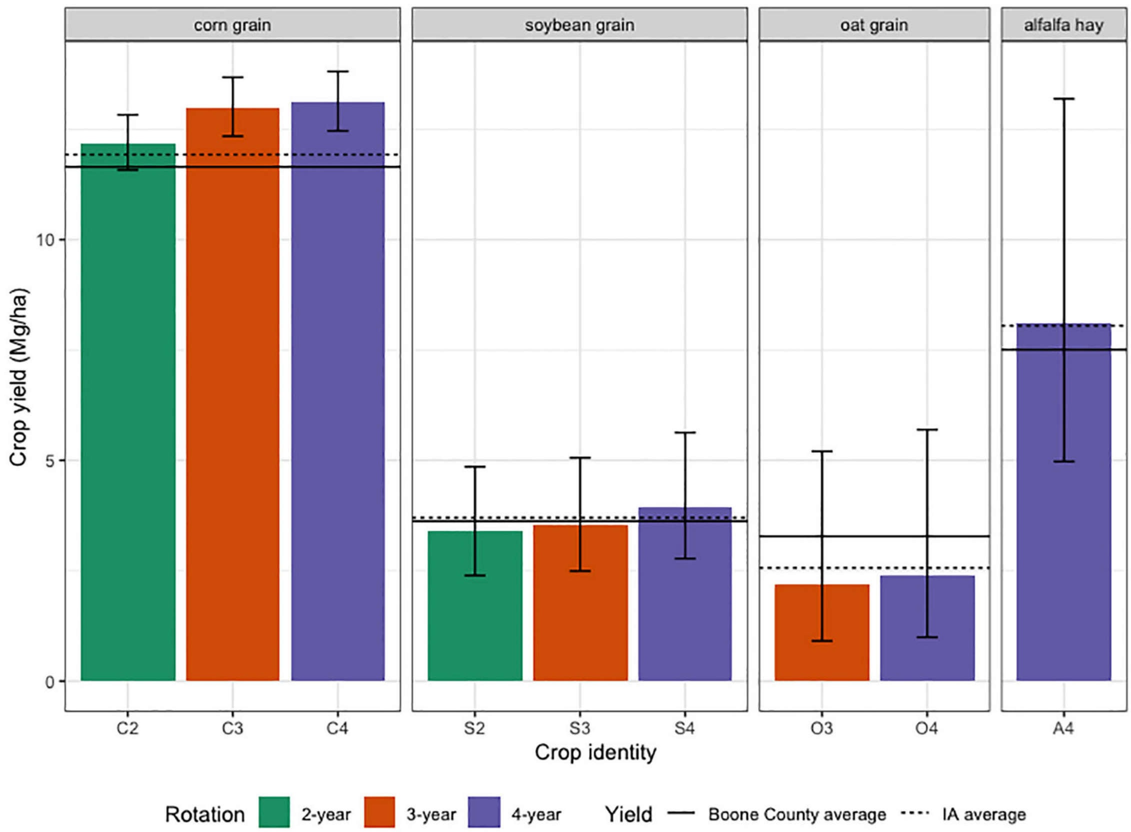

FIGURE 1 | Mean crop yields by rotation from 2017 to 2020. The color-coded bars show crop yields (Mg ha^{-1}) in the experiment plots. The error bars show the 95% confidence intervals. The solid horizontal lines show mean yields for Iowa and dashed lines show mean yields for Boone County. Corn, soybean, and alfalfa yields in the experiment were averaged over four years, oat grain yields in the experiment were averaged over 2017, 2019, and 2020 because in 2018 oat was harvested for hay. Because county-specific alfalfa hay yields in 2019 and 2020 were unavailable at this writing, Boone County alfalfa yield (solid line) was averaged over 2017 and 2018 and Iowa hay yield (dashed line) was averaged from all county-based values in 2017 and 2018 and two state-based values in 2019 and 2020.

Y is the year,
ϵ_{il} is the residual.

As each crop species was fitted with a model, the crop identity represents the rotation effect only. With these models (Equations 2, 3, and 4), we tested the hypothesis that the yield of the same crop species (corn, soybean, and oat) did not differ between rotations. Crop yields were then contrasted between rotations to examine the magnitude of any significant difference.

RESULTS

A lack of any obvious bias in plots of residuals vs. predicted values suggested that the analysis models fit the data well. Diagnosis plots made with `ggResidpanel` (version 0.3.0, Goode and Rey, 2019) are available in Model Diagnosis.

How Did Rotation System and Corn Weed Management Affect Crop Yields?

Results of the experiment indicated that crop diversification and reduced use of herbicides were not associated with lower crop yields (**Table 2**). Averaged over 4 years, soybean was the only crop whose yield was affected by rotation ($p = 0.0191$, **Table 2**). Soybean yield was 16% higher in the 4-year rotation than in the 2-year rotation ($p = 0.0181$). Crop yields in the experiment were as high or higher than the averages for the state of Iowa and Boone County (**Figure 1**).

How Did Rotation System, Crop Species, and Corn Weed Management Affect Community Ecological Indices?

Crop identity (i.e., rotation system x crop phase combination) affected weed community stand density evenness ($p = 0.0064$) and richness ($p = 0.0123$, **Table 3C**) and aboveground mass diversity ($p = 0.0007$, **Table 3A**), evenness ($p = 0.0003$, **Table 3B**), and richness ($p = 0.013$). For all the differences in ecological indices, crop types were more influential than rotations, with larger differences found between crop types than between rotations (**Figure 2**, **Tables 4**, **5**).

In general, the hypothesis that "weed communities in the more diverse cropping systems are more diverse" was supported.

Averaged over crop phases within each rotation system (**Table 4A**), the weed community stand diversity index for the

TABLE 3 | ANOVAs of crop identity, corn weed management, and their interactive effects on weed community ecological indices.

Source of variation	df1	df2	Stand density		Aboveground mass	
			F	***p***	***F***	***p***
(A) Community diversity						
Crop ID	8	24	1.25	0.3116	5.22	0.0007
Corn weed management	1	3	0.21	0.6804	0.47	0.5439
Crop ID x Corn weed management	8	24	0.54	0.8182	1.35	0.2659
(B) Community evenness						
Crop ID	8	24	3.66	0.0064	5.87	0.0003
Corn weed management	1	3	0.24	0.6589	0.01	0.9414
Crop ID x Corn weed management	8	24	0.74	0.6547	0.47	0.8632
(C) Community richness						
Crop ID	8	24	3.23	0.0123	3.19	0.0130
Corn weed management	1	3	1.32	0.3330	1.59	0.2959
Crop ID x Corn weed management	8	24	0.71	0.6803	0.86	0.5635

Corn weed management: low herbicide or conventional. Crop ID: crop species and the cropping system in which it occurred: C2,corn in the 2-year rotation, C3, corn in the 3-year rotation; C4, corn in the 4-year rotation; S2, soybean in the 2-year rotation; S3, soybean in the 3-year rotation; S4, soybean in the 4-year rotation; O3, oat in the 3-year rotation; O4, oat in the 4-year rotation; A4, alfalfa in the 4-year rotation.

3-and 4-year rotation systems was comparable with that in the 2-year rotation ($p = 0.0535$ and $p = 0.1575$, respectively). For the individual crops (**Table 4B**), the weed stand density diversity index was comparable among rotations ($p > 0.05$). For different crop types (**Table 4C**), the weed community stand density diversity index in the average for the cool-season crops (O3, O4, and A4) was 1.2-fold greater than that in the average for the warm-season crops (C2, S2, C3, S3, C4, and S4) ($p = 0.0145$), but similar between the warm-season and cool-season crops in the same rotations ($p = 0.4666$ and $p = 0.0987$, respectively). The weed stand density diversity index was similar between oat and alfalfa ($p = 0.7762$).

Averaged over crop phases within the same rotation (**Table 5A**), the weed community aboveground mass diversity index was different between the 2-year rotation and the average of the 3- and 4-year rotations ($p = 0.0148$), and between the 3- and 4-year rotations ($p = 0.0209$). Averaged over the corn and soybean phases within the same rotation (**Table 5A**), the weed community aboveground mass diversity index was similar between rotations ($p = 0.4217$ and $p = 0.2426$, respectively). For the individual crops (**Table 4B**), the weed community aboveground mass diversity index was comparable between rotations, except for oat ($p = 0.0351$). For different crop types (**Table 4C**), the weed community aboveground mass diversity index in the cool-season crops average was 1.3-fold greater than that in the warm-season crops averages, overall ($p < 0.0001$), and was 1.23-fold and 1.27-fold greater in the cool-season than that in the warm-season crops in the 3-year ($p = 0.034$) and 4-year rotation ($p = 0.0037$), respectively. The weed community aboveground mass diversity index was comparable between oat and alfalfa ($p = 0.2583$).

The hypothesis that "weed communities in the more diverse cropping systems are more even" was partially supported (**Figures 2B,E**). However, a lower community evenness index can occur because the presence of rarer species decreases the overall evenness index (Stirling and Wilsey, 2001). More details to support this concept are presented later (**Figures 3C,D**).

Averaged over crop phases within the same rotation (**Table 4A**), the weed community stand density evenness index in the 2-year rotation was 1.6-fold greater than that in the average of the 3- and 4-year rotations ($p = 0.006$), but comparable between the 3- and 4-year rotations ($p = 0.2802$). Averaged over the corn and soybean phases within the same rotation (**Table 4A**), the weed community stand density evenness index was comparable between rotations ($p = 0.1539$ and $p = 0.5031$, respectively). For the individual crops (**Table 4B**), the weed community stand density evenness index was comparable between rotations ($p > 0.05$). For different crop types (**Table 4C**), the weed community stand density evenness index in the cool-season crops average was half of that in the warm-season crops average ($p = 0.0002$) and half of that in the cool-season and warm-season crop in the 4-year rotation ($p = 0.0012$), but similar between the warm-season and cool-season crops in the 3-year rotation ($p = 0.4418$). The weed community stand density evenness index was comparable between oat and alfalfa ($p = 0.8986$).

Averaged over crop phases within the same rotation (**Table 5A**), the weed community aboveground mass evenness index in the 2-year rotation was 1.65-fold greater than that in the average of 3- and 4-year rotations ($p = 0.0012$), but similar between the 3- and 4-year rotations ($p = 0.0802$). Averaged over the corn and soybean phases within the same rotation (**Table 5A**), weed community aboveground mass evenness index was comparable between rotations ($p = 0.1081$ and $p = 0.8682$, respectively). For the individual crops (**Table 4B**), the weed community aboveground mass evenness index was comparable between rotations ($p > 0.05$), except for oat ($p = 0.0189$). The weed community aboveground mass evenness index in the warm-season crops average was twice that of the cool-season crops average ($p < 0.0001$). The weed community aboveground mass evenness index in the warm-season crops was twice that of the cool-season crops in the 4-year rotation ($p = 0.0002$), but comparable between the warm-season and cool-season crops in the 3-year rotation ($p = 0.141$), and between oat and alfalfa ($p = 0.5911$).

The hypothesis that "the weed communities in the more diverse cropping systems are more species-rich" was supported.

Averaged over crop phases within the same rotation (**Table 4A**), the weed community stand density richness index was comparable in the 2-year rotation and in the average of the 3- and 4-year rotations ($p = 0.1819$), but the stand density richness index in the 3-year was 0.77 that of the 4-year rotation ($p = 0.0257$). Averaged over the corn and soybean phases within the

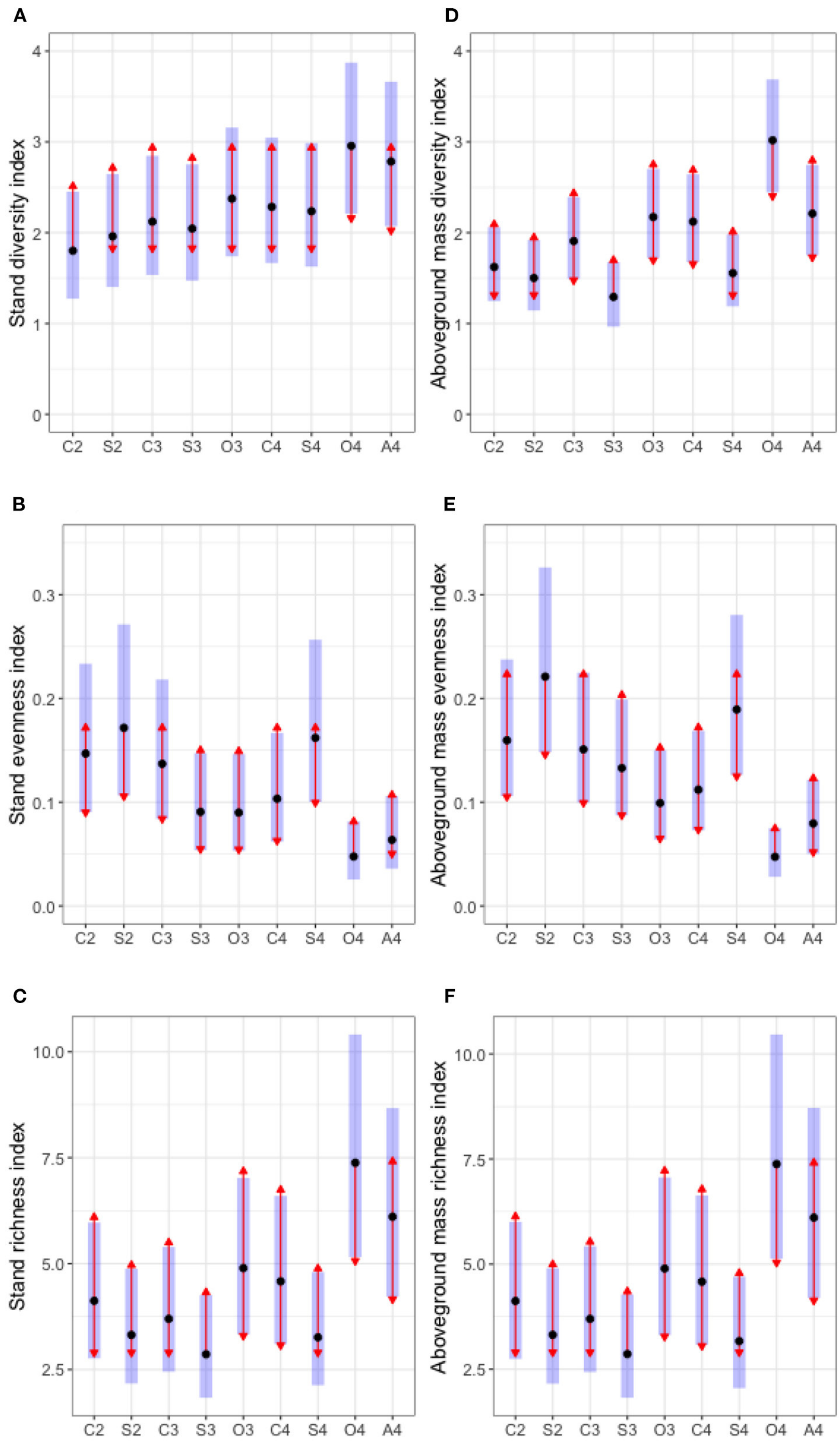

FIGURE 2 | Weed community stand diversity **(A)**, evenness **(B)**, richness **(C)**, community aboveground diversity **(D)**, evenness **(E)**, and richness **(F)**. The abbreviations on the x-axis are crop identities, which are the combinations of the first letter in crop species names and the rotation in which it occurred (C2-corn in the 2-year rotation, C3-corn in the 3-year rotation, C4- orn in the 4-year rotation, S2-soybean in the 2-year rotation, S3-oybean in the 3-year rotation, S4-soybean in the 4-year rotation, O3-oat in the 3-year rotation, O4-oat in the 4-year rotation, and A4-alfalfa in the 4-year rotation). The black dots are estimated marginal means. The blue bars are 95% confidence intervals. The red arrows reflect comparisons among means. Overlapping arrows indicate non-significant differences.

same rotation (**Table 4A**), weed community aboveground mass richness index was comparable between the 2-year rotation and the 3- and 4-year rotations average ($p = 0.7996$) and between the 3- and 4-year rotations ($p = 0.3469$). For individual crops (**Table 4B**), the weed community stand density richness index was comparable between rotations (p > 0.05). For different crop types (**Table 4C**), the weed stand density richness index in the cool-season crops average was 1.33-fold greater that of the warm-season crops average ($p = 0.0003$). Within the 4-year rotation, the weed stand density richness index in the cool-season was 1.58-fold greater than that in the warm-season crops ($p = 0.0034$). The weed stand density richness was comparable between the warm-season and cool-season crops in the 3-year rotation ($p = 0.0725$) and between oat and alfalfa ($p = 0.9499$).

The same patterns of difference and similarity of weed community richness index calculated with aboveground mass was observed (**Table 5**).

General Description of the Weed Flora

Overall, 34 weed species were identified during the 4 years of data collection (**Table 6**). Seven weed species, SETFA (*Setaria faberi*), AMATA (*Amaranthus tuberculatus*), CHEAL (*Chenopodium album*), DIGSA (*Digitaria sanguinalis*), ECHCG (*Echinochloa crus-galli*), SETLU (*Setaria glauca*), and TAROF (*Taraxacum officinale*) made up 94.4% of the total weed density and 94.0% of the total weed biomass (**Figures 3C,D**).

How Did Rotation, Crop Species, and Corn Weed Management Affect Weed Community Density and Growth?

Crop identity affected weed community stand density ($p < 0.0001$) and weed community aboveground mass ($p = 0.0057$), but corn weed management and its interaction with crop identity did not affect weed community stand density or biomass ($p > 0.05$) (**Tables 4**, **5**). Weed community stand density and aboveground mass in each crop identity category, averaged over blocks, years, and corn weed management regimes, are presented in **Figures 3A,B**. Contributions by the dominant species are presented in **Figures 3C,D**. Contrasts for the effects of rotation systems, rotation system within individual crops, and crop types on community stand density and aboveground mass are shown in **Table 7C**.

Weed community density and aboveground mass of the 3- and 4-year systems averages were comparable to those of the 2-year system ($p = 0.058$ and $p = 0.9451$, respectively; **Table 7B1**). The weed community density in the 4-year rotation was 2.5-fold greater than that in the 3-year rotation ($p = 0.0368$), but the community aboveground mass was comparable between the 3- and 4-year rotations.

For the individual crops (**Table 7B2**), increased rotation diversity tended to decrease weed density and aboveground mass in corn and soybean and increase weed abundance in oat, but these changes were not significant ($p = 0.6354$ and $p = 0.4041$ for corn, $p = 0.1834$ and $p = 0.0739$ for soybean, and $p = 0.3955$ and $p = 0.335$ for oat). The patchiness of weeds, which was reflected in the high standard error values, might have caused the lack of significance for these inconclusive trends.

For different crop types, weed community density and aboveground mass were comparable between the warm-season crops (corn and soybean) and between the cool-season crops (oat and alfalfa) (**Table 7B3**). Overall, the average weed community

TABLE 6 | List of weed species (in alphabetical order) found from 2017 to 2020 field seasons.

Bayer code	Scientific name	Life cycle
(A) Dicotyledon species		
ABUTH	*Abutilon theophrasti* Medicus	Annual
AMARE	*Amaranthus retrofelxus* L.	Summer annual
AMATA	*Amaranthus tuberculatus* (Moq.) Sauer var. *rudis*	Summer annual
AMBEL	*Ambrosia artemissifolia* L.	Erect, branching, summer annual
ARFMI	*Arctium minus* (Hill) Bernh.	Biennial
CHEAL	*Chenopodium album* L.	Erect summer annual
CIRAR	*Cirsium arvense* (L.) Scop.	Rhizomatous perennial
CIRVU	*Cirsium vulgare* (Savi) Tenore	Biennial
EPHHT	*Euphorbia humistrata* Engelm. ex Gray	Mat-forming summer annual
EPHMA	*Euphorbia maculata* L.	Mat-forming summer annual
EUPHY	*Eupatorium hyssopifolium* L.	Summer annual
MORAL	*Morus alba* L.	Perennial shrub
PHYSU	*Physalis subglabrata* Mackenz. and Bush	Rhizomatous perennial
PLAMA	*Plantago major* L.	Rosette-forming perennial
POLPE	*Polygonum perfoliatum* L.	Spiny summer annual vine
POLPY	*Polygonum pensylvanicum* L.	Ascending much-branched summer annual
POROL	*Portulaca oleracea* L.	Prostrate mat-forming summer annual
SOLPT	*Solanum ptycanthum* Dun.	Erect branching summer annual
SONAR	*Sonchus arvensis* L.	Rhizomatous perennial
TAROF	*Taraxacum officinale* Weberin Wiggers	Tap-rooted perennial
(B) Monocotyledon species		
AGRRE	*Elytrigia repens* (L.) Nevski	Rhizomatous perennial
BROTE	*Bromus tectorum* L.	Summer or winter annual
CCHPA	*Cenchrus longispinus* (Hack.) Fern.	Summer annual
CONAR	*Convolvulus arvensis* L.	Rhizomatous perennial
CYPES	*Cyperus esculentus* L.	Rhizomatous perennial
DACGL	*Dactylis glomerata* L.	Clump-forming perennial
DIGSA	*Digitaria sanguinalis* (L.) Scop.	Summer annual
ECHCG	*Echinochloa crus – galli* (L.) Beauv.	Summer annual
ERBVI	*Eriochloa villosa* (Thunb.) Kunth	Erect summer annual
FESSP	*Festuca* spp.	Clump-forming perennial
PANCA	*Panicum capillare* L.	Summer annual
PANDI	*Panicum dichotomiflorum* Michx.	Summer annual
SETFA	*Setaria faberi* Herrm.	Clump-forming, erect summer annual
SETLU	*Setaria glauca* (L.) Beauv.	Clump-forming, erect summer annual

TABLE 4 | Weed stand density ecological indices contrast significance.

Contrast	Diversity index		Evenness index		Richness index	
	Ratio	*p*	Ratio	*p*	Ratio	*p*
(A) Rotation system effects						
[(C2+S2)/2] vs. [(C3+S3+O3+C4+S4+O4+A4)/7]	0.85	0.0535	1.60	0.0060	0.86	0.1819
[(C3+S3+O3)/3] vs. [(C4+S4+O4+A4)/4]	0.90	0.1575	1.18	0.2802	0.77	0.0257
[(C2+S2)/2] vs. [(C3+S3+C4+S4)/4]	0.91	0.2749	1.28	0.1539	1.03	0.7996
[(C3+S3)/2] vs. [(C4+S4)/2]	0.95	0.5824	0.88	0.5031	0.87	0.3469
(B) Rotation system effects within individual crops						
C2 vs. [(C3+C4)/2]	0.88	0.2836	1.20	0.4406	1.00	0.9985
C3 vs. C4	0.95	0.7231	1.28	0.3757	0.84	0.3966
S2 vs. [(S3+S4)/2]	0.94	0.6331	1.36	0.2065	1.06	0.7212
S3 vs. S4	0.94	0.6711	0.60	0.0746	0.91	0.6260
O3 vs. O4	0.85	0.2716	1.66	0.0757	0.70	0.0912
(C) Crop type effects						
[(O3+O4+A4)/3] vs. [(C2+S2+C3+S3+C4+S4)/6]	1.20	0.0145	0.55	0.0002	1.53	0.0003
O3 vs. [(C3+S3)/2]	1.09	0.4666	0.83	0.4418	1.38	0.0725
[(O4+A4)/2] vs. [(C4+S4)/2]	1.19	0.0987	0.49	0.0012	1.58	0.0034
[(O3+O4)/2] vs. A4	0.97	0.7762	1.03	0.8986	0.99	0.9499

The abbreviations on the contrast column are crop identities, which are the combinations of the first letter in crop species names and the rotation in which it occurred. C2, corn in the 2-year rotation; C3, corn in the 3-year rotation; C4, corn in the 4-year rotation; S2, soybean in the 2-year rotation; S3, soybean in the 3-year rotation; S4, soybean in the 4-year rotation; O3, oat in the 3-year rotation; O4, oat in the 4-year rotation; A4, alfalfa in the 4-year rotation.

TABLE 5 | Weed aboveground mass ecological indices contrast significance.

Contrast	Diversity index		Evenness index		Richness index	
	Ratio	*p*	Ratio	*p*	Ratio	*p*
(A) Rotation system effects						
[(C2+S2)/2] vs. [(C3+S3+O3+C4+S4+O4+A4)/7]	0.85	0.0148	1.65	0.0012	0.86	0.1967
[(C3+S3+O3)/3] vs. [(C4+S4+O4+A4)/4]	0.87	0.0209	1.27	0.0802	0.78	0.0309
[(C2+S2)/2] vs. [(C3+S3+C4+S4)/4]	0.95	0.4217	1.28	0.1081	1.04	0.7694
[(C3+S3)/2] vs. [(C4+S4)/2]	0.91	0.2426	0.97	0.8682	0.88	0.3930
(B) Rotation system effects within individual crops						
C2 vs. [(C3+C4)/2]	0.87	0.1425	1.20	0.3825	1.00	0.9985
C3 vs. C4	0.93	0.5084	1.31	0.2780	0.84	0.4035
S2 vs. [(S3+S4)/2]	1.03	0.7219	1.36	0.1543	1.08	0.6801
S3 vs. S4	0.90	0.3166	0.72	0.1905	0.93	0.7075
O3 vs. O4	0.79	0.0351	1.83	0.0189	0.70	0.0957
(C) Crop type effects						
[(O3+O4+A4)/3] vs. [(C2+S2+C3+S3+C4+S4)/6]	1.30	<0.0001	0.51	<0.0001	1.54	0.0003
O3 vs. [(C3+S3)/2]	1.23	0.0340	0.73	0.1410	1.38	0.0766
[(O4+A4)/2] vs. [(C4+S4)/2]	1.27	0.0037	0.48	0.0002	1.60	0.0032
[(O3+O4)/2] vs. A4	1.11	0.2583	0.89	0.5911	0.99	0.9506

The abbreviations on the contrast column are crop identities, which are the combinations of the first letter in crop species names and the rotation in which it occurred. C2, corn in the 2-year rotation; C3, corn in the 3-year rotation; C4, corn in the 4-year rotation; S2, soybean in the 2-year rotation; S3, soybean in the 3-year rotation; S4, soybean in the 4-year rotation; O3, oat in the 3-year rotation; O4, oat in the 4-year rotation; A4, alfalfa in the 4-year rotation.

density in the cool-season crops was 26-fold greater than that in the warm-season crops ($p < 0.0001$), and the average weed community aboveground mass in cool-season crops was 16-fold greater than that in warm-season crops ($p = 0.0001$). In the 3-year rotation, the weed stand community stand in oat (O3) was 11.5-fold greater than the average in corn and soybean (C3 and S3) ($p = 0.0012$), but the weed community aboveground mass was comparable between O3 and the average of the C3 and S3 phases ($p = 0.1502$). In the 4-year rotation, the weed community stand density in the average of oat and alfalfa (O4 and A4) was 36-fold greater than the average of the corn (C4) and soybean (S4) phases ($p < 0.0001$), and the average weed biomass for the O4 and A4 phases was 29-fold greater than that for the C4 and S4 phases ($p < 0.0001$).

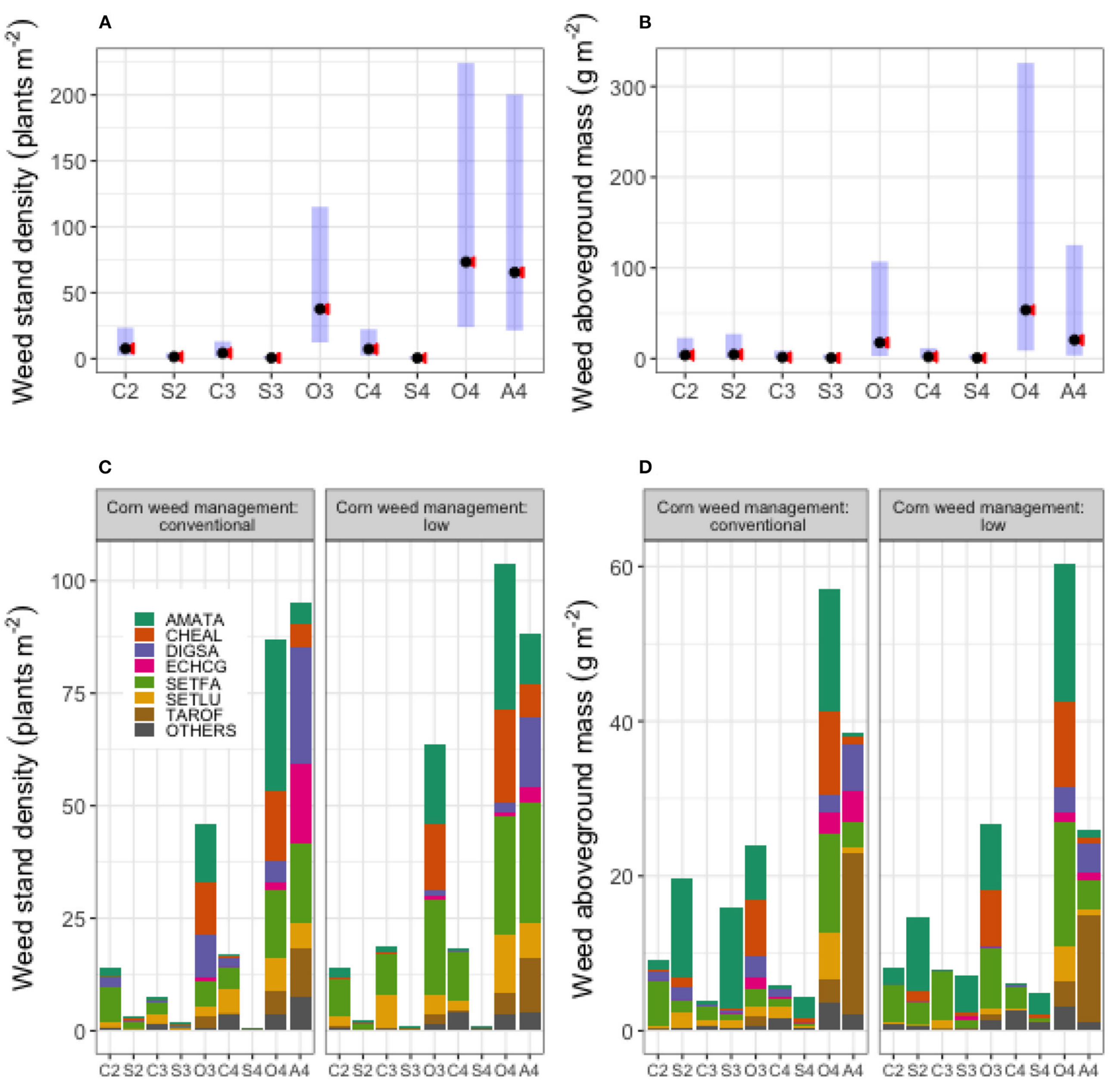

FIGURE 3 | In **(A,B)** weed community stand density and aboveground mass were averaged over four blocks, 4 years, and two corn weed management regimes; the black dots are estimated marginal means; the blue bars are 95% confidence intervals; the red arrows reflect the comparisons among means; overlapping arrows indicate non-significant differences. In **(C,D)** the contribution of the seven most abundant weed species and the rarer species (species ordered eighth and above grouped in OTHERS) in each crop identity, averaged over four blocks and 4 years, are ordered alphabetically. The abbreviations on the x-axis are crop identities, which are the combinations of the first letter in crop species names and the rotation in which it occurred (C2-corn in the 2-year rotation, C3-corn in the 3-year rotation, C4-corn in the 4-year rotation, S2-soybean in the 2-year rotation, S3-soybean in the 3-year rotation, S4-soybean in the 4-year rotation, O3-oat in the 3-year rotation, O4-oat in the 4-year rotation, and A4-alfalfa in the 4-year rotation). The less abundant weed species which made up 6% of the whole community are grouped in OTHERS. The means displayed on **(A,B)** were estimated marginal means, calculated based on the analysis model (with `emmip` (version 1.7.2, Lenth, 2022) function) but the means displayed on **(C,D)** were arithmetic means, calculated from the data so they are slightly different.

How Did Rotation, Crop Species, and Corn Weed Management Affect Individual Weed Species Abundance?

The hypothesis that "including oat and alfalfa in rotations with corn and soybean will reduce the density and aboveground mass of noxious weed species in corn and soybean" was partially supported. Crop identity affected individual density of seven most abundant weed species but corn weed management affected that of two weed species only, i.e., DIGSA and SETFA ($p = 0.0189$ and $p = 0.0196$, resepectively; **Table 8**. Among those seven weed

TABLE 7 | Community density and aboveground mass ANOVA and contrasts.

(A) ANOVA			**Stand density**		**Aboveground mass**	
Source of variation	**df1**	**df2**	***F***	***p***	***F***	***p***
Crop ID	8	24	12.22	<0.0001	3.74	0.0057
Corn weed management	1	3	2.13	0.2402	0.02	0.8900
Crop ID x Corn weed management	8	24	1.66	0.1613	0.99	0.4660
(B) Contrasts			**Ratio**	***p***	**Ratio**	***p***
(B1) Rotation system effects						
[(C2+S2)/2] vs. [(C3+S3+O3+C4+S4+O4+A4)/7]			0.42	0.0580	0.96	0.9451
[(C3+S3+O3)/3] vs. [(C4+S4+O4+A4)/4]			0.40	0.0368	0.42	0.1712
(B2) Rotation system effects within individual crops						
C2 vs. [(C3+C4)/2]			1.38	0.6354	2.30	0.4041
C3 vs. C4			0.59	0.4969	0.73	0.7853
S2 vs. [(S3+S4)/2]			2.49	0.1834	6.25	0.0739
S3 vs. S4			1.19	0.8248	1.04	0.9731
O3 vs. O4			0.51	0.3955	0.33	0.3350
(B3) - Crop type effects						
[(C2+S2)/2] vs. [(C3+S3+C4+S4)/4]			1.85	0.2032	3.79	0.0665
[(C3+S3)/2] vs. [(C4+S4)/2]			1.69	0.3426	3.54	0.1274
[(O3+O4+A4)/3] vs. [(C2+S2+C3+S3+C4+S4)/6]			26.10	<0.0001	16.00	0.0001
O3 vs. [(C3+S3)/2]			11.50	0.0012	4.29	0.1502
[(O4+A4)/2] vs. [(C4+S4)/2]			35.90	<0.0001	28.70	0.0003
[(O3+O4)/2] vs. A4			0.80	0.7440	1.49	0.6870

The abbreviations in the contrast column are crop identities, which are the combinations of the first letter in crop species names and the rotation in which it occurred. C2, corn in the 2-year rotation; C3, corn in the 3-year rotation; C4, corn in the 4-year rotation; S2, soybean in the 2-year rotation; S3, soybean in the 3-year rotation; S4, soybean in the 4-year rotation; O3, oat in the 3-year rotation; O4, oat in the 4-year rotation; A4, alfalfa in the 4-year rotation.

species, the aboveground mass of four (CHEAL, DIGSA, SETFA, and TAROF) were affected by crop identity, but none was affected by corn weed management (**Table 8**). The magnitude of difference in stand density and aboveground mass were the most pronounced between crop types (**Table 9**). The main-plot effects concerning crop identity on individual species responses are elaborated below.

The cool-season crops were responsible for AMATA stand density differences, but those differences were not strong enough to be apparent between rotation averages. AMATA stand density and aboveground mass were comparable among all rotation systems averaged over crop phases ($p > 0.05$), among rotations for the same crop species ($p > 0.05$), and within the same crop type across rotations ($p > 0.05$). Averaged over the same crop types (warm-season or cool-season), AMATA stand density in cool-season was 12.25-fold greater than that in warm-season crops ($p = 0.0001$), but AMATA aboveground mass was comparable in cool-season and warm-season crops ($p = 0.0906$). Within the same rotation, AMATA stand density was 11-fold ($p = 0.0143$) and 23-fold ($p = 0.0003$) greater in the cool-season than in the warm-season crops overall averages, but AMATA aboveground mass was comparable in these crop environments ($p = 0.2355$ and $p = 0.0493$, respectively).

The cool-season crops, especially oat were responsible for CHEAL stand density and aboveground mass differences between rotation averages. CHEAL stand density and aboveground mass were 4-fold ($p = 0.008$) and 5-fold ($p = 0.199$) greater in the average of the 3- and 4-year rotations than in the 2-year rotation, but comparable between the 3- and 4-year rotations ($p = 0.9195$ and $p = 0.6114$, respectively). CHEAL stand density and aboveground mass were comparable between rotations for the same crop species ($p > 0.05$) and within the warm-season crops ($p > 0.05$). CHEAL stand density and aboveground mass were 38-fold ($p < 0.0001$) and 204-fold ($p < 0.0001$) greater in the cool-season crops than in the warm-season crops overall averages; 67-fold ($p < 0.0001$) and 571-fold ($p < 0.0001$) greater in the cool-season crop than in the warm-season crops average of the 3-year rotation; and 37-fold ($p < 0.0001$) and 232-fold ($p < 0.0001$) greater in the cool-season crop than in the warm-season crops average of the 4-year rotation. CHEAL stand density and aboveground mass were 11-fold ($p = 0.0001$) and 96-fold ($p = 0.0001$) greater in oat than in alfalfa.

The cool-season crops, especially alfalfa were responsible for DIGSA stand density and aboveground mass differences between rotation averages. DIGSA stand density in the average of the 3- and 4-year rotations was two-fold greater than in the 2-year rotation ($p = 0.0072$) and 5-fold greater in the 4-year rotation than in the 3-year rotation ($p < 0.0001$). DIGSA aboveground mass was comparable between the 2-year and the average of the 3- and 4-year rotations ($p = 0.1098$), but 14-fold greater in the 4-year than in the 3-year rotations ($p = 0.0001$). DIGSA stand density and aboveground mass were comparable between rotations for the same crop species ($p > 0.05$), except for oat ($p =$

TABLE 8 | Treatment effects on the stand density and aboveground mass of the seven most abundant weed species, listed alphabetically.

Source of variation	df1	df2	Stand density		Aboveground mass	
			F	***p***	***F***	***p***
(A) AMATA						
Crop ID	8	24	3.72	0.0058	1.52	0.2016
Corn weed management	1	3	0.73	0.4566	4.19	0.1333
Crop ID x Corn weed management	8	24	0.96	0.4886	1.09	0.4052
(B) CHEAL						
Crop ID	8	24	22.06	<0.0001	15.53	<0.0001
Corn weed management	1	3	2.10	0.2430	0.56	0.5097
Crop ID x Corn weed management	8	24	1.59	0.1808	1.07	0.4180
(C) DIGSA						
Crop ID	8	24	15.52	<0.0001	8.14	<0.0001
Corn weed management	1	3	21.52	0.0189	16.44	0.0270
Crop ID x Corn weed management	8	24	1.25	0.3126	0.78	0.6237
(D) ECHCG						
Crop ID	8	24	2.61	0.0328	2.20	0.0645
Corn weed management	1	3	5.80	0.0952	4.84	0.1150
Crop ID x Corn weed management	8	24	1.16	0.3615	1.04	0.4348
(E) SETFA						
Crop ID	8	24	8.78	<0.0001	4.22	0.0028
Corn weed management	1	3	20.91	0.0196	13.96	0.0334
Crop ID x Corn weed management	8	24	0.70	0.6892	1.04	0.4371
(F) SETLU						
Crop ID	8	24	3.09	0.0154	1.33	0.2774
Corn weed management	1	3	4.44	0.1257	3.28	0.1681
Crop ID x Corn weed management	8	24	1.11	0.3930	0.83	0.5875
(G) TAROF						
Crop ID	8	24	49.63	<0.0001	35.81	<0.0001
Corn weed management	1	3	0.61	0.4914	0.33	0.6067
Crop ID x Corn weed management	8	24	0.74	0.6553	1.20	0.3382
(H) OTHERS						
Crop ID	8	24	4.76	0.0014	2.35	0.0503
Corn weed management	1	3	1.99	0.2533	2.27	0.2288
Crop ID x Corn weed management	8	24	0.07	0.9997	0.43	0.8939

All the other weeds species were grouped into OTHERS. Corn weed management: low herbicide or conventional. C2, corn in the 2-year rotation; C3, corn in the 3-year rotation; C4, corn in the 4-year rotation; S2, soybean in the 2-year rotation; S3, soybean in the 3-year rotation; S4, soybean in the 4-year rotation; O3, oat in the 3-year rotation; O4, oat in the 4-year rotation; A4, alfalfa in the 4-year rotation.

0.0062 and $p = 0.0032$). DIGSA stand density and aboveground mass were 10- and 27-fold greater in the cool-season crop averages than in the warm-season crops averages, 20-fold ($p = 0.0001$) and 103-fold ($p = 0.0001$) greater in the cool-season crops than in the warm-season crops of the 4-year rotation, but comparable between cool-season and warm-season crops of the 3-year rotation ($p = 0.0603$ and $p = 0.3924$, respectively). DIGSA stand density and aboveground mass were 14-fold ($p = 0.0001$) and 33-fold ($p = 0.0001$) greater in alfalfa than in oat.

ECHCG responses generally were similar to those of AMATA. ECHCG stand density and aboveground mass were comparable between all rotation averages ($p > 0.05$), between rotations for the same crop species ($p > 0.05$), within the same crop type between rotations ($p > 0.05$), and within the 3-year rotation ($p > 0.05$). Averaged over the same crop types, ECHCG stand density and aboveground mass were 4-fold ($p = 0.0003$) and 10-fold ($p = 0.0012$) greater in the cool-season than in the warm-season crops. Within the 4-year rotation, ECHCG stand density and aboveground mass were 5-fold ($p = 0.0014$) and 18-fold ($p = 0.0031$) greater in the cool-season than in the warm-season crops.

The cool-season crops were responsible for SETFA stand density and aboveground mass differences, but those differences were not strong enough be apparent between rotation averages. SETFA stand density and aboveground mass were comparable between all rotation averages ($p > 0.05$), between rotations for the same crop species ($p > 0.05$), within the warm-season crops between rotations ($p > 0.05$), and within the cool-season crops ($p > 0.05$).

TABLE 9 | Contrast of stand density and aboveground mass of the seven most abundant weed species.

	AMATA		CHEAL		DIGSA		ECHCG		SETFA		SETLU		TAROF	
Contrast of the main-plot effect	**Ratio**	***p***	**Ratio**	***p***	**Ratio**	***p***	**Ratio**	***p***	**Ratio**	***p***	**Ratio**	***p***	**Ratio**	***p***
(A) Stand density														
(A1) Rotation system effects														
[(C2+S2)/2] vs. [(C3+S3+O3+C4+S4+O4+A4)/7]	0.74	0.6105	0.28	0.0008	0.42	0.0072	0.57	0.1170	0.64	0.3011	0.50	0.1569	0.24	<0.0001
[(C3+S3+O3)/3] vs. [(C4+S4+O4+A4)/4]	0.81	0.7077	0.97	0.9195	0.21	<0.0001	0.55	0.0834	0.49	0.0927	0.44	0.0827	0.19	<0.0001
[(C2+S2)/2] vs. [(C3+S3+C4+S4)/4]	2.45	0.1746	1.37	0.3889	1.14	0.6798	0.98	0.9584	1.86	0.1906	0.70	0.4944	0.95	0.8129
[(C3+S3)/2] vs. [(C4+S4)/2]	1.76	0.4533	1.45	0.3823	0.69	0.3213	0.97	0.9384	0.75	0.5877	0.74	0.6234	0.84	0.5105
(A2) Rotation system effects within individual crops														
C2 vs. [(C3+C4)/2]	2.33	0.3598	1.42	0.4995	0.93	0.8818	0.97	0.9497	1.56	0.5010	0.56	0.4277	1.02	0.9547
C3 vs. C4	1.65	0.6368	1.31	0.6510	0.54	0.2466	0.89	0.8579	0.49	0.3501	0.49	0.3990	0.87	0.6923
S2 vs. [(S3+S4)/2]	2.58	0.3065	1.33	0.5837	1.40	0.4658	0.99	0.9915	2.21	0.2337	0.88	0.8628	0.88	0.6958
S3 vs. S4	1.87	0.5543	1.60	0.4312	0.88	0.8088	1.04	0.9444	1.14	0.8620	1.14	0.8780	0.82	0.5914
O3 vs. O4	0.32	0.2890	0.74	0.6212	0.21	0.0062	0.46	0.2130	0.59	0.4848	0.33	0.2006	0.09	<0.0001
(A3) Crop type effects														
[(O3+O4+A4)/3] vs. [(C2+S2+C3+S3+C4+S4)/6]	12.25	0.0001	38.15	<0.0001	10.11	<0.0001	3.60	0.0003	9.85	<0.0001	2.48	0.0404	24.33	<0.0001
O3 vs. [(C3+S3)/2]	10.94	0.0143	67.07	<0.0001	2.43	0.0630	1.94	0.2248	11.32	0.0010	1.05	0.9435	4.33	0.0001
[(O4+A4)/2] vs. [(C4+S4)/2]	23.36	0.0003	36.99	<0.0001	20.08	<0.0001	4.82	0.0014	11.63	0.0001	2.96	0.0798	53.81	<0.0001
[(O3+O4)/2] vs. A4	3.71	0.1606	10.75	0.0001	0.07	<0.0001	0.49	0.1954	1.17	0.8068	0.37	0.1812	0.17	<0.0001
(B) Aboveground mass														
(B1) Rotation system effects														
[(C2+S2)/2] vs. [(C3+S3+O3+C4+S4+O4+A4)/7]	3.10	0.3402	0.21	0.0199	0.36	0.1098	0.35	0.1417	0.93	0.9245	0.46	0.3588	0.07	<0.0001
[(C3+S3+O3)/3] vs. [(C4+S4+O4+A4)/4]	1.30	0.8168	1.33	0.6414	0.07	0.0001	0.32	0.1040	0.56	0.4497	0.39	0.2420	0.05	<0.0001
[(C2+S2)/2] vs. [(C3+S3+C4+S4)/4]	9.26	0.0893	2.30	0.2315	1.60	0.4852	0.89	0.8841	3.54	0.1566	0.58	0.5502	0.86	0.7608
[(C3+S3)/2] vs. [(C4+S4)/2]	2.83	0.4799	2.43	0.2676	0.54	0.4264	1.00	0.9958	0.94	0.9537	0.89	0.9148	0.67	0.4810
(B2) Rotation system effects within individual crops														
C2 vs. [(C3+C4)/2]	7.45	0.2696	2.21	0.4167	1.06	0.9499	1.02	0.9882	2.81	0.4070	0.48	0.5668	0.94	0.9237
C3 vs. C4	1.78	0.7802	1.70	0.6372	0.40	0.3994	0.69	0.7630	0.39	0.5131	0.50	0.6404	0.85	0.8309
S2 vs. [(S3+S4)/2]	11.50	0.1821	2.39	0.3720	2.40	0.3571	0.79	0.8252	4.47	0.2329	0.71	0.7847	0.80	0.7378
S3 vs. S4	4.50	0.4709	3.49	0.2708	0.73	0.7772	1.44	0.7687	2.27	0.5667	1.59	0.7516	0.54	0.4336
O3 vs. O4	0.14	0.3486	0.53	0.5666	0.03	0.0032	0.10	0.0768	0.29	0.3941	0.12	0.1539	0.01	<0.0001
(B3) Crop type effects														
[(O3+O4+A4)/3] vs. [(C2+S2+C3+S3+C4+S4)/6]	6.11	0.0906	204.44	<0.0001	27.29	<0.0001	9.56	0.0012	15.00	0.0008	2.05	0.3316	389.81	<0.0001
O3 vs. [(C3+S3)/2]	8.70	0.2355	571.14	<0.0001	2.26	0.3924	2.54	0.3920	22.34	0.0180	0.47	0.5554	19.10	0.0002
[(O4+A4)/2] vs. [(C4+S4)/2]	20.20	0.0493	231.64	<0.0001	102.80	<0.0001	17.54	0.0031	22.79	0.0045	3.18	0.2706	1482.81	<0.0001
[(O3+O4)/2] vs. A4	28.24	0.0724	94.46	0.0001	0.03	0.0008	0.64	0.6762	5.38	0.1818	0.43	0.5132	0.05	0.0001

Weed species are listed alphabetically. The abbreviations on the contrast column are crop identities, which are the combinations of the first letter in crop species names and the rotation in which it occurred. C2, corn in the 2-year rotation; C3, corn in the 3-year rotation; C4, corn in the 4-year rotation; S2, soybean in the 2-year rotation; S3, soybean in the 3-year rotation; S4, soybean in the 4-year rotation; O3, oat in the 3-year rotation; O4, oat in the 4-year rotation; A4, alfalfa in the 4-year rotation.

Averaged over the same crop types, SETFA stand density and aboveground mass were 10-fold ($p < 0.0001$) and 15-fold ($p = 0.0008$) greater in the cool-season than in the warm-season crops. Within the same rotation, SETFA stand density and aboveground mass were 11-fold to 23-fold greater in the cool-season than in the warm-season crops (**Table 9**).

SETLU stand density and aboveground mass were comparable in most pairs of comparison ($p > 0.05$), except that SETLU stand density was 2.5-fold greater in the cool-season crops average than in the warm-season crops average ($p = 0.0404$).

The cool-season crops, especially oat were responsible for TAROF stand density and aboveground mass differences between rotation averages. TAROF stand density and aboveground mass in the 3- and 4-year rotations average were 4-fold ($p < 0.0001$) and 14-fold ($p < 0.0001$) greater than those in the 2-year rotation. TAROF stand density and aboveground mass in the 3-year rotation were and 5-fold ($p < 0.0001$) and 20-fold ($p < 0.0001$) greater than those in the 4-year rotation. TAROF stand density and aboveground mass were comparable among the warm-season crops between rotations and within the same crops between rotations ($p > 0.05$), except in oat ($p < 0.0001$). TAROF stand density and aboveground mass were 24-fold ($p < 0.001$) and 390-fold ($p < 0.0001$) greater in cool-season than in warm-season crop averages, 4-fold ($p = 0.0001$) and 20-fold ($p = 0.0002$) greater in oat than in corn and soybean averages in the 3-year rotation, and 54-fold ($p < 0.0001$) and 1,483-fold ($p < 0.0001$) greater in the cool-season crops than in the warm-season crops in the 4-year rotation. TAROF stand density and aboveground mass were 6-fold ($p < 0.0001$) and 20-fold ($p = 0.0001$) greater in oat than in alfalfa.

DISCUSSION

Diversification of cropping systems led to increased weed community aboveground mass and stand density, increased weed community diversity and species richness, and decreased weed community evenness. Increased weed abundance was not associated with reduced crop yield. Crop identity in the present experiment had the strongest influence on the response variables. This observation is consistent with previous studies in which crop identity showed the strongest influence on weed community characteristics (Légère et al., 2005; Smith and Gross, 2007). The observation that crop yields were not correlated with increased weed aboveground mass suggests that low amounts of weed biomass can be tolerated, rather than the commonly desired weed-free condition (Zimdahl, 2012). Tolerating greater weed abundance can create some risks of resurgence by formerly prevalent weed species or outbreak of highly adapted introduced species under favorable conditions (Mohler, 2001). Consequently, weed growth and weed community composition should be monitored frequently to keep weed infestations at tolerable levels and to detect risks for future seasons. As weeds develop resistance to herbicides, weed eradication is likely to be increasingly impractical for technical, financial, and environmental reasons (Stewart et al., 2011; Brookes and Barfoot, 2013), making the monitoring of weed communities a critically important component of weed management.

Ryan et al. (2010) found that weeds growing in a preceding crop phase of a sequence affected the subsequent seedbank more strongly than the seedbank influenced the emerged weed flora; the investigators attributed this a filtering effect of crop management on weed seed production by mixed-species communities. The four years of data presented here did not reveal any weed species that might become aggressive in the presence of oat, red clover, and alfalfa. Following the critical period for weed control concepts described by Knezevic et al. (2002), weed control measures were applied in corn and soybean at their early establishment stages, but were not necessary in oat's early establishment because the most abundant weed species in this experiment site were summer annuals, whose emergence and establishment are synchronized with corn and soybean. Planting oat and red clover after soybean (in the 3-year rotation), instead of circling back to corn (as in the 2-year rotation), disrupted life cycles of those summer annual weeds. An extended disruption was also imposed in the 4-year rotation with the oat/alfalfa intercrop in year 3 and established alfalfa in year four. Frequent hay cuts severely suppressed weed species with erect stature, such as AMATA, CHEAL, and ECHCG, but did not significantly affect other species such as TAROF, SETFA, and SETLU. TAROF is a low stature weed, which was not as severely suppressed in alfalfa and oat as were AMATA, CHEAL, and ECHCG. SETFA and SETLU are clump-forming species that are less likely to be affected by harvest machinery. In oat, AMATA, CHEAL, ECHCG, SETFA, and SETLU, like most of the summer annual weeds at the experiment site, were in their early vegetative stages at oat harvest (Buhler and Hartzler, 2001; Cordeau et al., 2017). By the weed sampling dates, those weeds were physically severed once by the oat harvest combine, or twice by additional stubble clipping if the weed pressure was deemed high.

Tolerating higher amount of weeds might increase the risk of crop damage if weeds can serve as alternative hosts to pathogens (Wisler and Norris, 2005; Mohler and Johnson, 2009). However, soybean sudden death syndrome (SDS), caused by the soil-borne pathogen *Fusarium virguliforme* (Hartman et al., 2015), had its incidence and severity reduced due to cropping system diversification within the present experiment (Leandro et al., 2018). Among the currently recognized *Fusarium virguliforme* alternative hosts that were present at the experiment site, crops, such as alfalfa and red clover are considered symptomatic while weeds such as lambsquarter and pigweed asymptomatic (Kolander et al., 2012). Taking the findings of Kolander et al. (2012) and Leandro et al. (2018) together, it is more likely that crops played more important roles than weeds in SDS outbreaks and that cropping system diversification can control the risk of SDS outbreak effectively.

Differences in weed responses to cropping systems and management practices were more pronounced in aboveground mass than in stand density (**Tables 4**, **5**), which implied that rotation significantly affected weed growth but not weed emergence. These observations matched the general pattern reported by Weisberger et al. (2019). We attributed the observed community composition shift to the differences in crop phenology and required management practices between the warm-season crops (corn and soybean) and the cool-season crops (oat and alfalfa) (Gaba et al., 2014; Weisberger et al., 2019). In the present study, the magnitude of difference in sowing dates between soybean and oat seeded with red clover or alfalfa (60 days), as compared to that of corn and soybean (14 days), could be the largest contributor to reductions of weed density.

We considered the weed management programs in the 3- and 4-year rotations effective because the crop yields at our experiment site were comparable between rotations (**Table 2**) and to averages for the state of Iowa and Boone County (**Figure 1**). In the 2-year rotation, the net saved amount of herbicide between the low and conventional herbicide regimes was 13% as soybean plots were all treated with conventional weed management practices. The mass of herbicide active ingredients was reduced further in the 3- and 4-year rotations as corn and soybean were supplemented with oat, red clover, and alfalfa. For example, a 3-year rotation with corn under the low herbicide regime saved 42% of herbicide active ingredients as compared to the 2-year rotation with corn under conventional weed management; and the 4-year rotation with corn under low herbicide weed management saved 57% of herbicide active ingredients as compared to the 2-year rotation with corn under conventional weed management. We also considered two weed management programs for the same crop equally effective because the crop yields were not significantly different between corn weed management regimes. In the corn phase of the rotation systems, a transition from conventional to low herbicide weed management reduced the mass of herbicide active ingredients by 80% over 4 years because herbicide was applied in a band half of the area planted to corn.

Weed community aboveground mass composition and individual aboveground mass responses to cropping system diversification suggested that the weed communities that were dominated by few competitive species in the corn and soybean phases of the 2-year rotation could be shifted to have more of the rarer, less aggressive species. Community shifts to rarer, less aggressive weed species were reflected in the significant differences in ecological indices between cool-season and warm-season crops. The reduction of herbicide use, especially during oat and alfalfa phases of the rotation allowed some rarer species to grow, and thus, higher species richness and lower evenness were observed in oat and alfalfa than in corn and soybean. Community evenness indices in warm-season crops were higher than those in cool-season crops because fewer weed species were found in corn and soybean. The experimental units with high evenness index values had species of similar abundance and competitiveness, such as AMATA and CHEAL. Although an even weed community is desirable because of reduced chances that one or a few species are dominantly competitive (Adeux et al., 2019), weed communities could also be evenly dominated by a few weed species like AMATA, with high competitiveness, high reproduction potential, and quick herbicide resistance development. Thus, careful monitoring is required.

It is noteworthy that the relative abundance of the top seven species appeared more even in oat and alfalfa than in corn and soybean (**Figure 3**). Weeds can emerge in pulses in response to changes in soil conditions (e.g., temperature and moisture), so emergence after weed control measures have been applied and any residual effects have dissipated could result in successful establishment. Among the seven most abundant species in this experiment, five were influenced more strongly by crop identity than by corn weed management (**Table 8**). This observation is consistent with previous findings that emphasized the role of crops in weed community shifts (Davis et al., 2005b; Smith and Gross, 2007; Owen, 2008; Fried et al., 2012).

Due to labor constraints, only eight quadrats were evaluated per experimental unit (eu), and the samples in the eight quadrats within the same eu were tallied to make one data point. By using Simpson's ecological indices, we have limited the sensitivity of the responses to sample size (Nkoa et al., 2015). With eight quadrats randomly spaced within an eu, we sought to control for the patchiness of weed communities (Cardina et al., 1997), but the list of weed species presented in this manuscript is likely to not be exhaustive of species at the experiment site. We suggest, however, that the responses of dominant weed species, which are more agronomically important than the rarer species, were representatively assessed because the effects of spatially separated blocks on responses were non-significant. Also due to labor constraints, individual plant weight was not assessed, so we could not explore how community evenness was affected by individual plant size and whether there was any relationship or coincidence between evenness and individual plant reproductive potential.

A community that is dominated by AMATA, CHEAL, DIGSA, ECHCG, SETFA, and SETLU is more concerning than one dominated by TAROF, as determined by the frequency that those species are regarded as problematic (Kruger et al., 2009; Prince et al., 2012), their seedbank persistence characteristics (Buhler and Hartzler, 2001; Davis et al., 2005a), and their invulnerability to the strongest control measures (Mohler, 2001; Culpepper, 2006). Further investigation of AMATA, CHEAL, DIGSA, ECHCG, SETFA, and SETLU population dynamics, including emergence patterns, survival throughout crop season, and reproductive potentials under various cropping systems could help guide efforts to regulate the timing of their emergence, limit their growth and reproductive potentials, and eventually deplete their seedbanks. The reproductive potential of AMATA was reduced substantially in cool-season crops as compared to warm-season crops (Nguyen and Liebman, accepted). Taking the finding of Nguyen and Liebman with those of Gaba et al. (2014) and Weisberger et al. (2019), it is likely that the cool-season crops in the present study served to deplete the soil seedbank by inducing seed loss through weed emergence and granivore activities (van der Laat et al., 2015), while reducing reproduction potential through growth suppression. As demonstrated for SETFA (Davis et al., 2003), retrospective analyses applied to aggressive weed species can contribute to understanding species responses to management practices and to tailoring management tactics and timing to target them.

Overall, we conclude that by monitoring aboveground weed communities, a track record of species aggressiveness and collective response to management is available, and thus, it could be easier to control risks of weed resurgence and outbreak. Coupling knowledge of aboveground weed communities with that of weed seedbank composition and abundance would further improve our ability to predict and manage weed communities (Forcella et al., 1992; Menalled et al., 2001; Forcella, 2003; Davis et al., 2005b).

DATA AVAILABILITY STATEMENT

The data from this present study is available at https://doi.org/10.25380/iastate.19111376.v2.

AUTHOR CONTRIBUTIONS

ML conceptualized and designed the experiment. HN collected the data and wrote the original draft of the manuscript. ML and HN finalized the manuscript. Both authors contributed to the article and approved the submitted version.

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