Weed community and corn yield variability in diverse management systems

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The effects of crop rotation and management system on annual variability in weed communities and crop yields were assessed in a 4-yr study in Michigan. Variability of the weed community and corn yields were assessed using the coefficient of variation (CV) and a multivariate dissimilarity index (Bray-Curtis) that accounted for changes in both weed species abundance and composition. The treatments included two rotations: continuous corn and a corn–corn–soybean–wheat rotation, and two management systems: conventional (CONV) and organic-based (ORG). Weed biomass was significantly higher in the ORG system; however, there was no effect of crop rotation on weed biomass or number of weed species in a treatment (species richness). Annual variability in weed community composition and structure was affected by both crop rotation and management system and was highest in the ORG rotation. In contrast to the weed community, variability in corn yield was highest in the least-diverse cropping system (CONV monoculture), despite that system having a more constant weed community. Corn yield in the ORG rotation was not significantly different from that in the CONV monoculture. Results of this study suggest that management aimed at increasing cropping system diversity may have additional effects on weed communities and crop yields beyond those commonly reported, and these may have important implications for the development of more efficient and sustainable weed and crop management practices.

Nomenclature: Corn, *Zea mays* L.; soybean, *Glycine max* (L.) Merr.; wheat, *Triticum aestivum* L.

Key words: Crop rotation, cover crops, diversity, ecosystem function, management systems, organic, weed community.

The relationship between taxonomic diversity and ecosystem functions (e.g., productivity, stability) has long been a topic of interest in ecology (Cottingham et al. 2001; Elton 1958; Hooper et al. 2005; MacArthur 1955) and may have important implications for the management of agricultural systems (Altieri 1999). Ecological theory and experimental evidence from a variety of ecosystems suggest that communities made up of many interacting species should be more stable (i.e., less temporally variable in terms of overall biomass or productivity) than simple communities made up of few interacting species. This theory also predicts that whereas stability at the community level (i.e., total community biomass) should increase with diversity, stability at the population level should decrease (Cottingham et al. 2001; Lehman and Tilman 2000; Tilman 1996)—that is, abundances of individual species may vary over time, but overall community biomass should remain relatively stable from year to year. It is thought that population-level variability helps maintain community stability because differential responses among species to environmental fluctuations compensate for the loss of other species, thus stabilizing aggregate ecological properties, such as community productivity, across time (Cottingham et al. 2001; Micheli et al. 1999; Tilman 1996; Tracy and Sanderson 2004). As more growers adopt agronomic practices that increase cropping system diversity, determining the degree to which these practices affect the temporal variability of weeds and crop yields may have important implications for the development of more efficient and sustainable weed and crop management prac-

tices (Davis et al. 2005; Helmers et al. 2001; Menalled et al. 2001).

Predicting weed abundance and its effects on crop yield is an important component of integrated weed management (Lutman et al. 1996). Weed communities that are less variable in terms of biomass or species composition may require fewer proactive control measures such as the use of broadcast herbicide applications (Maxwell and Luschei 2005). However, weed communities that vary in abundance or species composition from year to year may also impact other ecosystem processes, such as resource use efficiency (Tracy and Sanderson 2004) and maintenance of natural enemies (Showler and Greenberg 2003), and these too may affect weeds and crop yields (Altieri 1999). For example, Thorbek and Bilde (2004) found that changes in weed communities because of agricultural management led to reduced generalist, arthropod predator populations.

Whereas the degree of annual variability in weed communities may have important implications for the management of weeds and crops in agricultural ecosystems, much of the ecological theory concerning diversity and community stability has been developed within the context of spatial diversity and in less heavily managed systems (Cottingham et al. 2001; Schläpfer and Schmid 1999). In many agricultural systems, however, diversity is both spatial and temporal, and little is known about the effect of the temporal component of diversity (number of different crops or cover crops included in a rotation) or different agricultural management systems have on the variability of weed communities or crop yields.

Here, we report results of a study comparing how management systems (conventional and organic-based with cover crops) and crop rotation (continuous monoculture and a 4-yr corn–corn–soybean–wheat rotation) affects annual variability in weed communities and corn yields. We tested the hypothesis that aggregate properties of the weed community (total biomass, community structure), as well as crop yields, should be less variable in more diverse cropping systems that have a greater number of potential ecological interactions (organic management systems and crop rotations) compared with simpler cropping systems with fewer potential ecological interactions (conventional systems and continuous monocultures). In accordance with ecological theory, we also expected that annual variability at the weed population level (species richness, species abundance) would be higher in more diverse cropping systems (Tilman 1996).

Materials and Methods

Study Site

The study was conducted at the Living Field Lab experimental (LFL) plots at the W. K. Kellogg Biological Station Long-Term Ecological Research (LTER) site of Michigan State University in Michigan. The LFL was established in 1993. Soils at the LFL site are a mixture of Kalamazoo (fine-loamy, mixed, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, mixed, mesic Typic Hapludalfs) sandy loams (Sanchez et al. 2001). In 1992, the site was planted to alfalfa. In 1993, rotation treatments were randomly assigned to plots within blocks under different management systems. The rotation treatments were continuous corn, and each phase of a 4-yr corn–corn–soybean–winter wheat rotation. Only continuous corn and the first-year corn phase of the rotation are compared in this study. The management systems examined in this study included a conventional (CONV) system that received full inputs of fertilizer and herbicides (broadcast applications) at rates recommended for the region (Sanchez et al. 2004) and an organic-based (ORG) system, which received composted dairy manure, but no synthetic chemical inputs. Each year in the ORG system, crimson clover (*Trifolium incarnatum* L.) was sown into standing corn in the continuous corn and the first corn phase of the rotation in late June; Italian ryegrass (*Lolium multiflorum* Lam.) was sown into the standing corn in the second corn phase; and red clover (*Trifolium pretense* L.) was frost seeded into standing winter wheat in late March. No cover crops were sown in the soybean phase of the rotation.

Weed management in the ORG system was via periodic rotary hoeing and row cultivation (2 to 4 times yr^{-1}). Plots in both systems were chisel plowed each year before planting. All treatments (input by rotation) were replicated four times. Blocks were separated by 8-m grass buffers. Subplots (rotation treatments) measured 15 by 9 m (CONV) and 15 by 4.5 m (ORG) and were not separated by buffers. Additional descriptions of the site and management can be found at lter.kbs.msu.edu/Data/LTER_Metadata.jsp/Dataset/KBS042.

Sampling

Weeds were harvested each year at peak biomass (early September 2001 to 2004) from a 0.25- by 1.0-m quadrat placed in each subplot. Because of the difference in size between the CONV and ORG subplots, two locations in each CONV and one location in each ORG replicate plot were sampled each year. The two subsamples from the CONV were averaged to determine subplot-level weed abundance. Within each subplot, the quadrat was placed perpendicular to the crop row to ensure equal sampling of row and interrow areas. The position of the quadrat within the plot was varied each year to avoid harvesting in the same location in successive seasons. All weeds rooted within the quadrat were clipped at ground level, sorted to species, and dried to constant biomass at 60 C. Dried biomass of each species was weighed to the nearest 0.01 g. Corn was harvested in October or November each year, and yields were calculated assuming moisture content of 15.5%.

Calculation of Variability

The coefficient of variation (CV) was used to assess annual variability in weed community biomass, species richness and abundance, and crop yield. To assess community stability (annual variation in total weed biomass), total weed biomass was calculated for each plot over the sampling period from 2001 to 2004. The CV was calculated as the standard deviation of weed biomass (2001 to 2004)/average weed biomass (2001 to 2004). The CV for quadrat-level species richness (number of weed species occurring in each quadrat) and corn yield were determined in the same manner. We assessed variability in species abundances (annual variation in the biomass of each species) by calculating the CV for each species in each plot. The species' CV's were then averaged for each plot (by summing and dividing by the overall number of species present in that plot).

In addition to variation in total weed biomass and species richness, we were also interested in a measure of community variability that would reflect overall community structure (the composition and abundance of species in the weed community). To obtain a multivariate measure of community variability, we calculated a matrix of Bray-Curtis dissimilarity coefficients (McCune and Grace 2002) using a data set containing species' biomass in each plot for each of the 4 yr. Before calculating the dissimilarity matrix, data were log (x + 0.01) transformed, and species occurring in less than 5% of the plot–years were deleted to reduce the influence of outliers and rare species. For each treatment replicate, we calculated dissimilarity in community abundance and composition from 1 yr to the next from 2001 to 2004. The average annual dissimilarity over the 4-yr period for each replicate was used as our measure of community-level variability.

Statistical Analysis

Analysis of variance was used to examine treatment effects on weed community and crop yield parameters. The model was a split-plot, randomized complete block (RCB) with three factors (block, management system, and rotation) and the system by rotation interaction. The block factor was considered random. Tests of main effects were performed with error terms appropriate for an RCB, split-plot design with management system as the whole plot factor and rotation as the subplot factor. Treatment means were compared with Tukey's HSD test at the 5% level of confidence

TABLE 1. Weed biomass, species richness, and crop yields (± SE; $n = 4$) in corn (2001 to 2004) in conventional (CONV) and organic (ORG) input systems in the Kellogg Biological Station (KBS) Long-Term Ecological Research (LTER) site. Rotations are continuous (CC) and rotated (R) corn (see text).

Inputs	Rotation	Year	Weed biomass		Species richness		Corn yield	
			(g m²)	SE	(0.25 m²)	SE	(kg ha⁻¹)	SE
CONV	CC	2001	49.0	16.3	5.0	0.8	3,444.4	307.4
		2002	3.4	2.4	3.9	0.4	5,966.6	81.6
		2003	16.5	11.2	4.5	0.8	4,843.5	407.8
		2004	4.9	2.7	5.0	0.6	8,683.2	332.5
	R	2001	41.7	8.6	7.9	0.8	5,483.5	382.7
		2002	2.6	0.8	7.3	1.8	7,666.8	131.8
		2003	12.2	3.8	4.8	0.4	7,026.9	144.3
		2004	23.5	14.2	4.1	0.9	10,019.6	439.2
ORG	CC	2001	126.5	70.6	6.3	0.6	4,084.4	294.9
		2002	168.1	90.5	5.5	1.0	5,025.5	840.7
		2003	180.7	112.6	5.8	0.5	4,580.0	301.2
		2004	347.8	76.6	10.3	0.8	3,049.2	401.5
	R	2001	32.1	5.4	6.3	0.3	4,887.4	652.5
		2002	178.5	46.3	10.8	1.5	6,060.7	671.3
		2003	1.0	0.5	3.3	0.5	7,058.3	232.1
		2004	554.2	185.0	9.5	0.7	4,122.0	727.8

when main effects were significant. All analyses were performed with SAS software[1] using the MIXED procedure (Little et al. 1996). Treatment effects on weed biomass and species richness were also analyzed, and these data were log and square root transformed, respectively, before analysis to improve homoscedasticity.

Results and Discussion

Weed Community Biomass and Richness

Weed community biomass and species richness varied from year to year in some treatments by as much as 500 and 300%, respectively (Table 1). There was substantial variation in precipitation and temperature over the course of the study (Figure 1) and this, no doubt, contributed to significant yearly variation in the weed community. Averaged across years, total weed community biomass was more than 10 times higher in the ORG compared with the CONV

system (ANOVA, system: $F_{1,3} = 186.10$, P < 0.001) (Figure 2a). There were no effects of crop rotation or the interaction between rotation and management system on total weed biomass (ANOVA, rotation: $F_{1,6} = 0.04$, P = 0.84; interaction: $F_{1,6} = 0.42$, P = 0.54).

There were only marginally significant effects of management system and crop rotation on weed species richness (ANOVA, system: $F_{1,3} = 8.59$, P = 0.06; rotation: $F_{1,6} = 4.59$, P = 0.076; interaction: $F_{1,6} = 1.35$, P = 0.2894) (Figure 3a). However, the identity of dominant weed species differed among the treatments (Table 2). Abundant weed species (species making up more than 10% of total weed biomass over the 4 yr) in the CONV system included smooth crabgrass, Carolina horsenettle, common chickweed, and common dandelion. In contrast, two annual dicots, common ragweed and common lambsquarters, were the most abundant in the ORG system, making up 30 and 35%, respectively, of the total biomass.
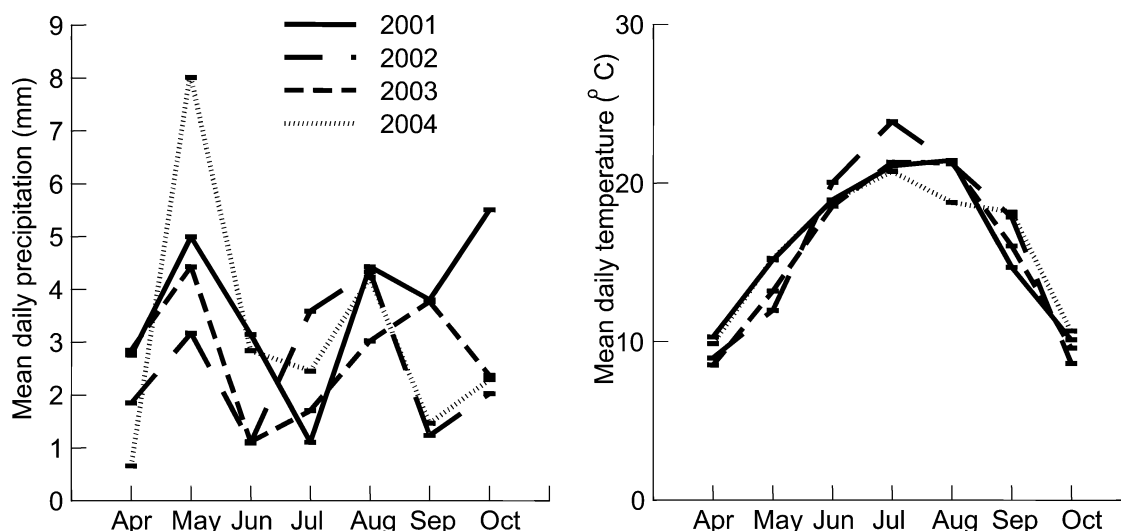

FIGURE 1. Mean daily precipitation and air temperature at the Kellogg Biological Station (KBS) Long-Term Ecological Research (LTER) for each month from April to October during the 4-yr study.
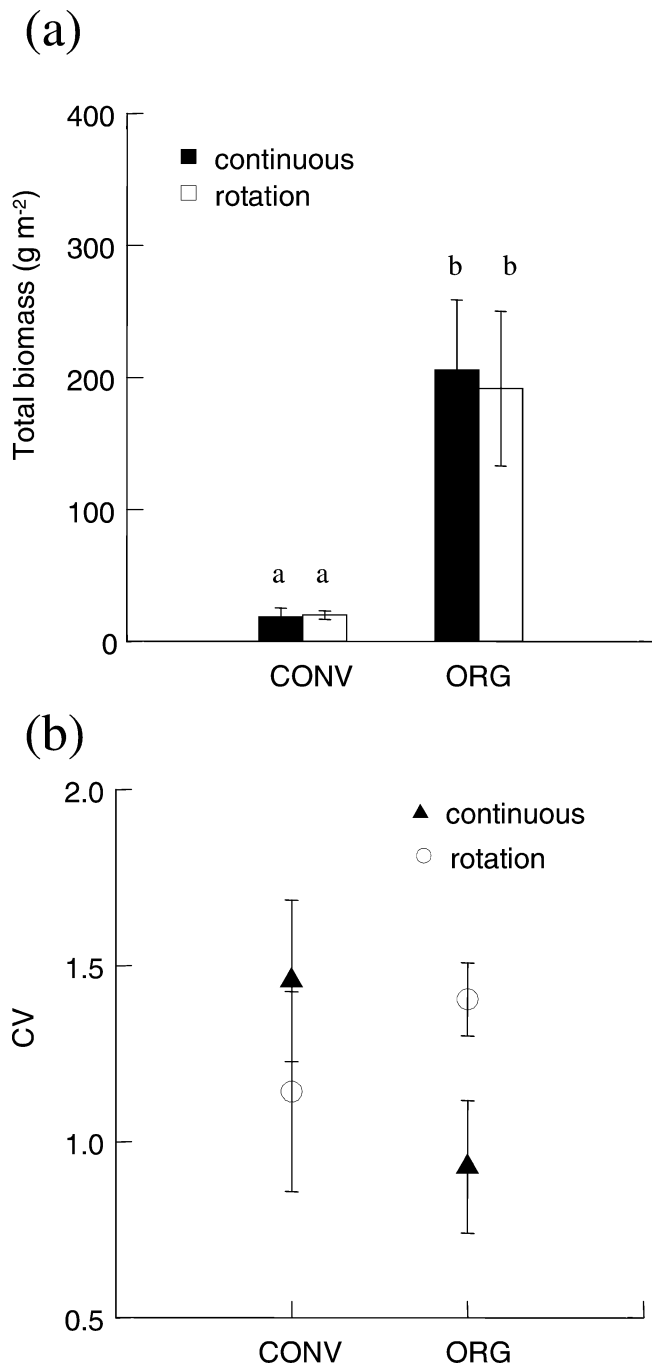
FIGURE 2. Effects of conventional (CONV) and organic (ORG) inputs and crop rotation on (a) weed community biomass from 2001 to 2004 and (b) interannual variability as measured by the coefficient of variation (CV). Error bars are 1 SE; biomass, $n = 16$; CV, $n = 4$. Bars sharing the same letter are not significantly different at the P = 0.05 level (Tukey–Kramer Test).
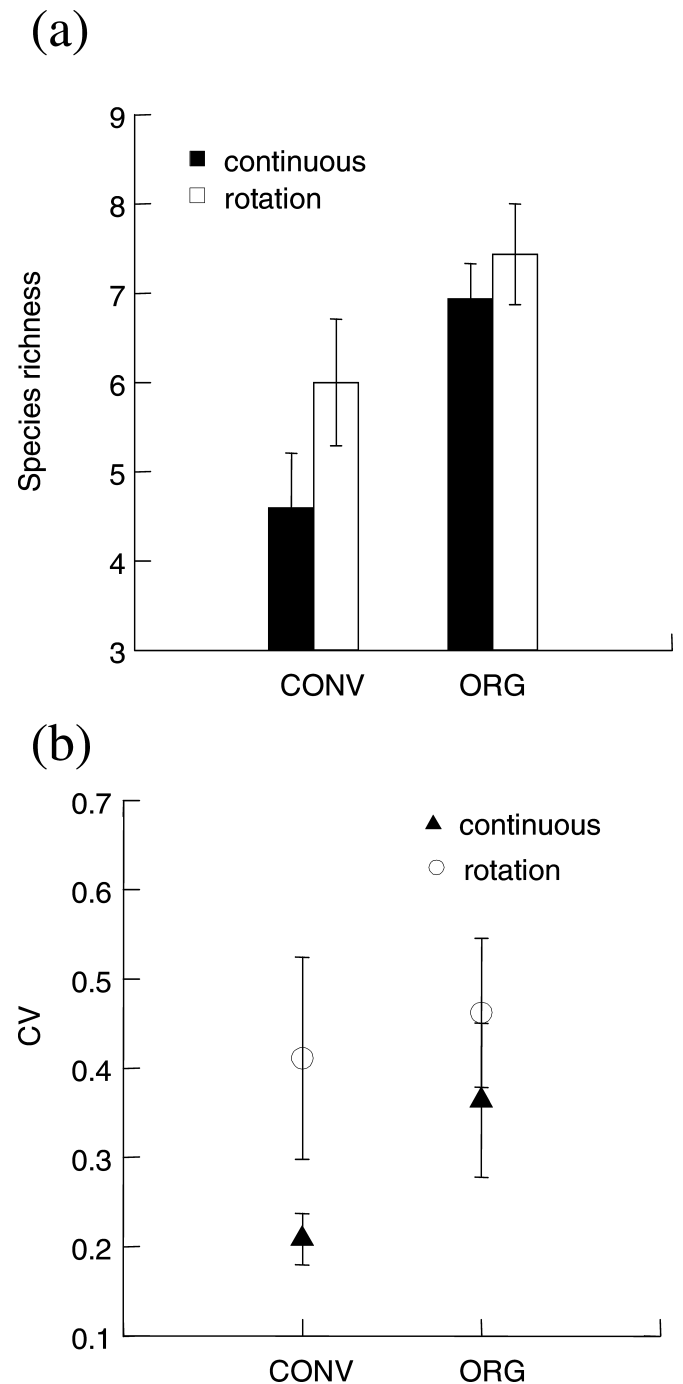
FIGURE 3. Effects of conventional (CONV) and organic (ORG) inputs and crop rotation on (a) weed community species richness from 2001 to 2004 and (b) interannual variability as measured by the coefficient of variation. Error bars are 1 SE; richness, $n = 16$; CV, $n = 4$. Bars sharing the same letter are not significantly different at the P = 0.05 level (Tukey–Kramer Test).

We had expected that weed communities in these two management systems would differ in total biomass because mechanical control measures are often less effective than herbicides at controlling weeds, particularly later in the growing season when crop canopy architecture precludes mechanical cultivation (Pleasant et al. 1994). Given the number of studies that have reported significant rotation effects on weed abundance and diversity (Liebman and Dyck 1993), the absence of a rotation effect in our study is somewhat surprising although not unique. Doucet et al. (1999) found few residual effects after 9 yr of a corn–soybean–wheat rotation on the composition and abundance of weeds following planting of corn in the 10th yr. Similarly, in an earlier study in the LFL, the previous crop, rather than the number of different crops in the rotation, was found to have the greatest impact on the abundance and composition of seeds in the soil (Smith and Gross, unpublished data).

TABLE 2. Weed species abundance in conventional (CONV) and organic (ORG) input systems under continuous (CC) and rotation (R) production. Values are mean percentage of total weed biomass and coefficient of variation (CV) averaged across years (2001 to 2004).

Species	Common name	CONV			ORG		
		Biomass (%)	CV CC	CV R	Biomass (%)	CV CC	CV R
Abutilon theophrasti Medik.	Velvetleaf				0.08	0.50	0.43
Amaranthus retroflexus L.	Redroot pigweed	0.04		0.45	7.97	0.48	0.50
Ambrosia artemisiifolia L.	Annual ragweed				30.40		0.43
Arabidopsis thaliana (L.) Heynh.	Mousearcress	0.60	0.35	0.40	0.05	0.43	0.40
Cardamine sp.	Bittercress	0.01	0.50				
Chenopodium album L.	Common lambsquarters	0.65	0.30	0.26	35.06	0.37	0.46
Conyza canadensis (L.) Cronq.	Canadian horseweed	0.00		0.50			
Daucus carota L.	Wild carrot	0.05		0.50			
Digitaria ischaemum (Schreb.) Schreb. ex Muhl.	Smooth crabgrass	14.98		0.50	0.17	0.45	0.46
Digitaris sanguinalis (L.) Scop.	Hairy crabgrass	1.20	0.37	0.34	0.03	0.37	0.43
Echinochloa crus-galli (L.) Beauv.	Barnyardgrass				0.81		0.50
Elymus repens (L.) Gould	Quackgrass	2.29	0.50	0.50	6.55	.40	0.47
Eragrostis cilianensis (All.) Vign. ex Janchen	Stinkgrass	0.00		0.50	0.00		0.50
Erigeron sp.	Fleabane				0.16	0.50	
Lamium sp.	Deadnettle	0.08	0.36	0.50	0.03	0.36	0.43
Mollugo verticillata L.	Green carpetweed	0.01		0.50			
Oxalis stricta L.	Common yellow woodsorrel	0.08		0.46		0.50	
Panicum dichotomiflorum Michx.	Fall panicgrass	0.87		0.45			0.50
Plantago major L.	Common plantain	0.03		0.50	0.25	0.50	
Poa sp.	Bluegrass	0.68	0.26	0.30	0.01	0.33	0.50
Polygonum aviculare L.	Prostrate knotweed				0.09	0.50	0.50
Polygonum convolvulus L.	Wild buckwheat				1.12	0.36	0.50
Polygonum persicaria L.	Spotted ladysthumb				2.35	0.44	0.50
Portulaca oleracea L.	Common purslane	0.03	0.50	0.40	0.00	0.50	
Rumex obtusifolius L.	Broadleaf dock	1.58	0.50	0.38	0.01		0.50
Setaria faberi Herrm.	Giant foxtail	0.02		0.50	2.68		0.50
Setaria pumila (Poir.) Roemer & J.A. Schultes	Cattailgrass	0.01		0.50	1.61	0.50	0.50
Setaria viridis (L.) Beauv.	Green foxtail	0.08		0.50	3.15	0.50	0.46
Solanum carolinense L.	Horsenettle	17.39	0.47	0.41	1.15	0.49	0.50
Solanum ptycanthum Dunal	Eastern black nightshade	0.00		0.50	0.05	0.50	0.48
Sonchus oleraceus L.	Annual sowthistle	0.07	0.50				
Stellaria media (L.) Vill.	Common chickweed	19.13	0.43	0.45	2.31	0.44	0.48
Taraxacum officinale G.H. Weber ex Wiggers	Common dandelion	37.83	0.38	0.39	1.11	0.24	0.42
Veronica persica Poir.	Birdseye speedwell	0.05		0.50	0.06	0.50	0.40
Veronica peregrina L.	Purslane speedwell	0.41	0.49	0.50	0.03	0.50	0.47

Weed Community Variability

We used a number of different metrics to characterize the level of annual variability in the weed community in response to the management system and rotation treatments, and although we detected differences among the treatments, they were not consistent with the predictions that we had developed, based on diversity–stability theory (Cottingham et al. 2001; Schläpfer and Schmid 1999). For example, based on ecological theory, we predicted that the more diverse rotation (ORG rotation) would be less prone to annual fluctuations in total weed biomass. However, we found that community-level variability was higher in the ORG rotation than in the ORG monoculture (ANOVA, interaction: $F_{1,6}$ = 26.09, P = 0.002; Tukey–Kramer P = 0.0188) (Figure 2b). We observed similar results when we analyzed weed community variability using a dissimilarity metric that combined data on both species abundance and composition (Bray–Curtis distance). The analysis indicated that weed communities were significantly more dissimilar in abundance and composition from year to year in the ORG rotation than the ORG or CONV monoculture or CONV rotation (system: $F_{1,3}$ = 20.97, P = 0.02; rotation: $F_{1,6}$ = 13.28, P = 0.011; interaction: $F_{1,6}$ = 5.56, P = 0.056) (Figure 4a). Taken together, these results suggest that both management system and crop rotation can affect weed community variability, but that crop rotation may be a more important driver of variability. Our results are similar to those of Davis et al. (2005), who examined weed communities over all phases of a corn–soybean–wheat rotation and reported little difference in the "constancy" of weed communities under conventional and organic management. This is in contrast, however, to a similar study conducted by Menalled et al. (2001), which reported weed communities in an organic rotation were more diverse and more constant compared with the same rotation under conventional management, suggesting that it may be difficult to make general predictions about how management systems will affect temporal variability in weed communities (Davis et al. 2005).

Diversity–stability theory predicts that as the number of species in a community increases, variability in the abundance of individual species should also increase (Tilman 1996). We found this to be true; weed population-level variability (average CV for individual species) was highest in the most-diverse cropping system (ORG rotation) and lowest in the least-diverse cropping system (CONV monoculture) (system: $F_{1,3}$ = 10.18, P < 0.05; rotation: $F_{1,6}$ = 8.01, P = 0.03; interaction: $F_{1,6}$ = 0.13, P = 0.73) (Table 2; Figure 4b). However, weed population- and community-level variability did not appear linked in the manner predicted by diversity–stability theory, as community-level variability was also higher in the ORG rotation (Figures 2b and 4a). This suggests that the link between weed population- and community-level stability may be weak in systems that are highly disturbed, such as agricultural fields that are annually tilled (Chesson and Huntly 1997).

Variability in community richness (CV richness) was not affected by either of the treatments (only a marginally significant effect of rotation: $F_{1,6}$ = 4.91, P = 0.07) (Figure 3b).
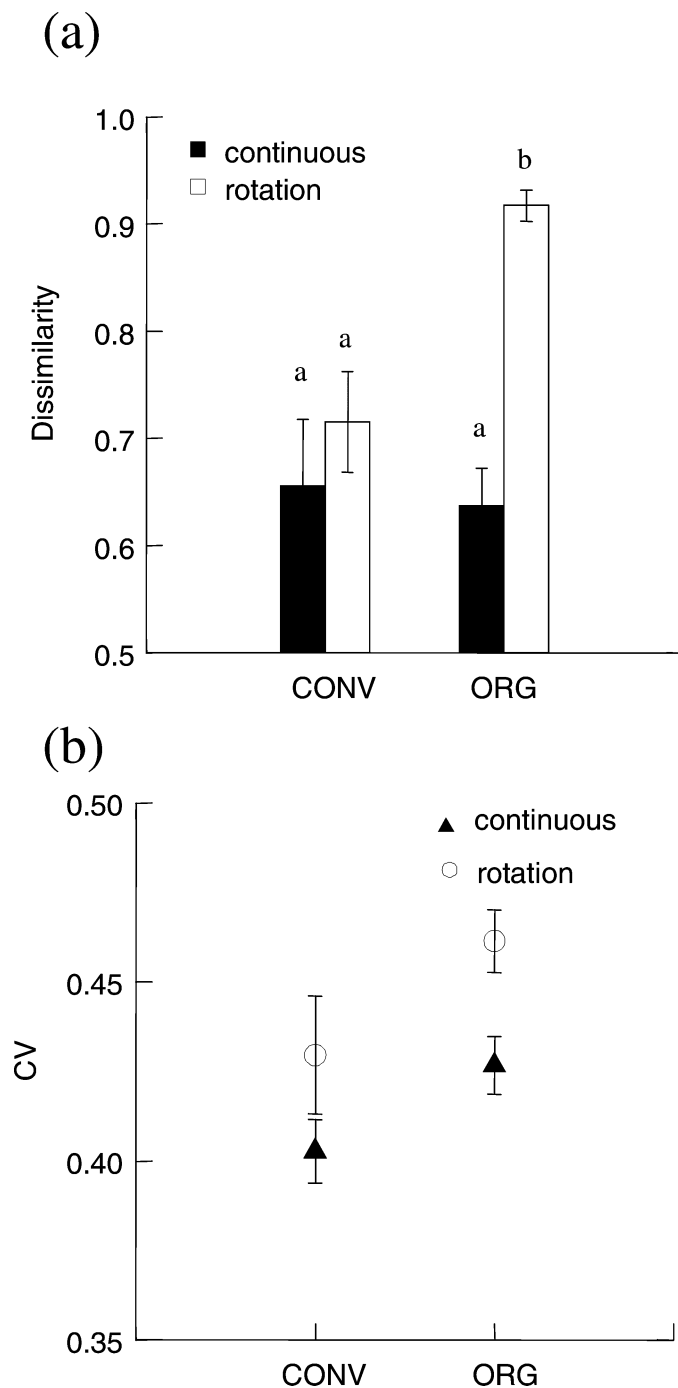
(a)

(b)

FIGURE 4. Effects of conventional (CONV) and organic (ORG) inputs and crop rotation on (a) weed community dissimilarity and (b) population-level interannual variability as measured by the coefficient of variation. Error bars are 1 SE; n = 4. Bars sharing the same letter are not significantly different at the P = 0.05 level (Tukey–Kramer Test).

Corn Yields and Variability

Corn yields also varied among years (Table 1), but average yields were highest in the CONV rotation, intermediate in the CONV monoculture and ORG rotation, and lowest in the ORG monoculture (system: $F_{1,3}$ = 19.81, P = 0.02; rotation: $F_{1,6}$ = 168.5, P < 0.0001; interaction: $F_{1,6}$ = 3.08, P = 0.13) (Figure 5a). As predicted from diversity–stability theory, we found that annual variability in corn yield was highest (highest CV) in the simpler cropping sys-
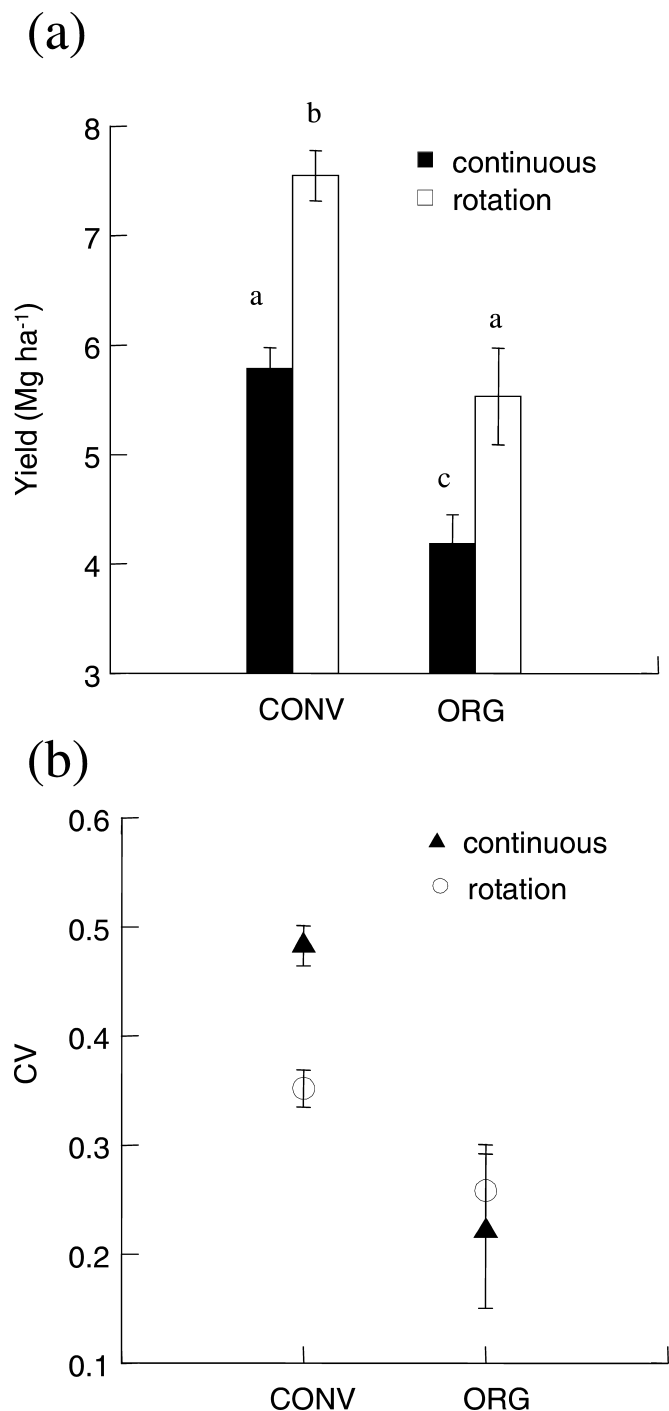
(a)

(b)

FIGURE 5. Effects of conventional (CONV) and organic (ORG) inputs and crop rotation on corn (a) yields from 2001 to 2004 and (b) interannual variability as measured by the coefficient of variation. Error bars are 1 SE; yield, $n = 16$; CV, $n = 4$. Bars sharing the same letter are not significantly different at the $P = 0.05$ level (Tukey–Kramer Test).

tem (CONV) (system: $F_{1,3} = 12.44$, $P = 0.04$; rotation: $F_{1,6} = 0.54$, $P = 0.49$; interaction: $F_{1,6} = 2.10$, $P = 0.20$) (Figure 5b). This result is in contrast to that of Tracy and Sanderson (2004) who found no relationship between the diversity of forage species and yield variability.

We found no relationship between variability in corn yields and variability in the weed community using any of the weed community variability indices as independent variables in a linear regression (data not shown).

Potential Explanations and Implications

One potential explanation for the lower annual variability in weed communities in the continuous corn compared with the rotation could be that within a block, continuous corn is planted in the same location each year. This is in contrast to rotated corn, which, because each phase of the rotation is present each year, occurs in a different location within the block each of the 4 yr. If spatial differences in weed species abundance between continuous corn and rotated corn were responsible for the observed differences in annual variation, then one would expect that within years, differences among replicates would be greater in the rotated corn treatments compared with continuous corn. To test this, we compared mean intrayear dissimilarity among replicate plots for each treatment using Bray–Curtis dissimilarity coefficients. We found that annual dissimilarity between replicates did not differ among the treatments (ANOVA, system: $F_{1,3} = 0.12$, $P = 0.75$; rotation: $F_{1,6} = 3.21$, $P = 0.123$; interaction: $F_{1,6} = 0.36$, $P = 0.571$), indicating that temporal autocorrelation was likely not responsible for the observed effects of rotation on community variability.

Another potential explanation may be that effects of diversity at the scale of the crop (crop diversity) are independent of factors that regulate stability in arable weed communities. This may be especially true when crop diversity is temporal (as in our crop rotations) and punctuated by high rates of annual disturbance. High rates of annual disturbance can lead to weak interactions among species (Chesson and Huntly 1997), and this may affect the compensatory responses among weed species necessary for generating stability (Cottingham et al. 2001).

If cropping system diversity per se has little direct effect on weed community variability, how can the differences in variability among the rotation treatments be explained? One possible answer may be the soil seed bank. Seeds in the seed bank contribute to most of the weeds emerging in a field in any given year, and the age of seeds in the seed bank can vary (Cavers and Benoit 1989). Seed age has been shown to affect germinability (Lindgren and Schaaf 2004) and can affect recruitment in some species (Rice and Dyer 2001). In our study, many of the weeds that emerged each year in the corn phase of the rotation likely germinated from seeds that were shed the last time corn appeared in the rotation (i.e., >2 yr earlier). This is in contrast to continuous corn, in which the majority of weeds likely emerged from seeds shed the previous year (Cavers and Benoit 1989). The seed bank in rotated corn also likely contained an abundance of species associated with winter wheat (Smith and Gross, unpublished data), which might also have contributed to compositional variation.

Our results suggest that in addition to the environmental costs often associated with conventional agricultural management (Robertson and Swinton 2005), crop yields in conventionally managed systems may be more prone to annual variability (Helmers et al. 2001). This is in contrast to the organic rotation, in which yields were significantly less variable and were just as high as those in the conventional monoculture, despite this system having greater weed abundance and weed community variability. This suggests that either the interactions among crops and weeds are lower in diversified organic systems (Stevenson et al. 1998) or that some other property of the weed community, which we did

not measure, contributes to increased crop yield stability. A better understanding of the factors contributing to temporal yield variation in row crops will help answer this question.

Sources of Materials

Acknowledgments

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