Influence of Cropping Systems on Soil Aggregate and Weed Seedbank Dynamics During the Organic Transition Period

Andrew T. Corbin,* Kurt D. Thelen, G. P. Robertson, and Richard H. Leep

ABSTRACT

Agronomic management during the 3-yr transition period to organic certification influences soil quality and the weed seedbank. We studied two cropping systems during the transition period and the first certified organic season. A 4-yr rotation of corn, soybean, wheat/alfalfa, corn (C-S-W/A-C) [*Zea mays* L., *Glycine max* (L.) Merr., *Triticum aestivum* L., *Medicago sativa* L.], produced under a more complex management that included manure and cover crop residue, was compared to a perennial based corn, alfalfa, alfalfa, corn (C-A-A-C) rotation. We compared soil aggregate size distribution and bulk density after Year 1 and on completion of the transition period. Weed seedbank populations were quantified through two seasons in the greenhouse. Weed surface density and aboveground weed biomass were quantified in the field. Over the course of the study, the percentage of large soil macroaggregates (>2000 μm size class) had 2.7 and 3.4-fold increase for the C-A-A-C and C-S-W/A-C treatments, respectively. The C-S-W/A-C system generated a 4.5-fold increase in aggregates of this class when wheat that was interseeded with alfalfa was harvested as forage. Bulk density decreased 14 and 6% for the C-S-W/A-C and the C-A-A-C systems, respectively. There was a 60 to nearly 300% increase in total weed seeds germinated in the greenhouse for the C-S-W/A-C system. This same system had a 60 to more than 500% decreased weed seedbank density in the field. We conclude from this study that either strategy can improve soil quality while the weed seedbank was better managed in the more complicated C-S-W/A-C system.

Weed management has been identified by organic farmers as the number one barrier to long-term success during the transition to certified production systems, with soil fertility and quality a close second (Walz, 2004). The aggregation of soil is an essential function in soil physicochemical and biological processes, and has been shown to influence soil quality through the protection of existing soil organic matter (SOM), moisture holding capacity, and soil nutrient retention (Angers and Giroux, 1996; Angers and Caron, 1998; Jiao et al., 2006). Additions of farmyard manure (FYM) to organic systems have been shown to enrich SOM directly and indirectly through improved soil properties such as increased numbers and distribution of soil macroaggregates, microfauna, macro- and micronutrients and improved crop yields (Edmeades, 2003; Ghoshal and Singh, 1995; Gupta et al., 1992; Jiang et al., 2006; Jiao et al., 2006; Mikha and Rice, 2004). Paré and colleagues (1999) have shown that the addition of stockpiled FYM to conventionally tilled systems significantly increased the percent of water stable aggregates compared with the same addition to a no-till system. Many studies show the opposite; in general, no-till systems result in increased total water stable soil aggregation (Denef et al., 2001; Grandy and Robertson, 2006; Green et al., 2005; Mikha and Rice, 2004; Park and Smucker, 2005; Six et al., 1999, 2000a, 2000b; Taboada-Castro et al., 2006; Zotarelli et al., 2007). While no-till systems can improve soil aggregation, they often rely heavily on herbicides for weed control, an unaccepted weed management practice in organic production.

Perennial legume rotations, such as alfalfa, have been shown to accumulate soil carbon faster than annual crop rotations. This is likely due to the plant residue quality and quantity as well as root biomass growth, C rhizodeposition of the legume and less reliance on tillage, all of which influence soil aggregation. Rates of carbon accumulation in perennial systems appear related to changes in soil aggregate size classes as these systems can modify decomposition dynamics by changing soil aeration, water dynamics, and aggregation, as well as the biochemistry and quantity of crop residues (Grandy and Robertson, 2007).

Research on organic production systems, which rely on mechanical weed management and the incorporation of green manures and FYM, have often shown increases in the weed seedbank as a result of viable weed seed return via incorporation of manures and reduced efficacy of mechanical over chemical weed control during the transition (Huxham et al., 2005; Riemens et al., 2007). Conversely, other studies have shown an increase in weed species richness with an overall decline in total weed populations under organic or pesticide-free systems (Liebman and Davis, 2000; van Elsen, 2000). The ecological relevance of weed species richness and population will vary based on landscape and

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Abbreviations: C-A-A-C, corn, alfalfa, alfalfa, corn; C-S-W/A-C, corn, soybean, wheat/alfalfa, corn; DTM, days to maturity; FSC, Farming Systems Center; FYM, farmyard manure; GDD, growing degree days; KBS, Kellogg Biological Station; LTER, long-term ecological research; NCDC, National Climatic Data Center; NOP, National Organic Program; OCIA, Organic Crop Improvement Association; OFRF, Organic Farming Research Foundation; OTA, Organic Trade Association; PET, potential evapotranspiration; SOM, soil organic matter.

agronomic practices, as biodiversity in agroecosystems depends on both. Weibull et al. (2003) found the correlations between species richness and landscape variables on a farm scale to be more important than those between species richness and management practices of farmers in disturbed organic systems.

Characteristics that are required of an ideal organic transition period include a low contribution to the weed seedbank, optimal nutrient levels for crop production, and maintenance of a healthy soil structure. The presence of these characteristics will allow optimum production once certification is obtained. During the transition period, organic producers must implement a crop rotation that includes but is not limited to sod, cover crops, green manure crops, and catch crops. The crop rotation is to provide functions which maintain or improve SOM content, manage deficient or excess plant nutrients, and provide erosion control (USDA, 2008b).

This study focuses on the changes in soil quality indicators (aggregate size distribution and bulk density), weed seedbank, and yield responses during the critical 3-yr transition period from a conventional system to a certified organic system. The objective of this research was to evaluate soil quality and weed seedbank responses following a complex, annual based (C-S-W/A-C) crop rotation and a simpler, perennial-based (C-A-A-C) crop rotation during the 3-yr conventional to certified organic transition period. These two cropping systems were chosen based on typical crops grown in the upper midwestern United States and the desire of organic row crop farmers to manage production mechanically (i.e., no hand weeding). The purpose of this study was based on the assumption that a producer has decided beforehand to make the transition from conventional to organic farming. Rather than strictly compare conventional vs. organic management for 3 yr (the required length of transition time for organic certification), we are contrasting two separate organic transitional methods and their effects on yield, weed seedbank dynamics, and soil quality characteristics. The fourth year (Year 1 of certification) was also investigated.

MATERIALS AND METHODS

Field Experiment

Experimental Site

Experimental plots were located at the W.K. Kellogg Biological Station (KBS) Farming Systems Center (FSC) site in southwest Michigan, (85°24′ W, 42°24′ N, elevation 288 m). The 20-yr average number of growing degree days (GDD; base 10°C) from May to October at this site is 1326 (KBS-LTER, 2008). Mean annual precipitation is 920 mm with about half as snow, and potential evapotranspiration (PET) exceeds precipitation for about 4 mo of the year. Average monthly temperatures range from −4.6°C in January to 23.1°C in July, with a mean annual temperature of 9.8°C (NOAA-NCDC, 2008).

Transitional treatments were established in 2003 in four replicated 0.04-ha plots (13.7 by 27.4 m) organized in a randomized complete block design. Blocking accounted for the two soil series identified at this site: Kalamazoo (fine-loamy, mixed, semiactive, mesic Typic Hapludalfs) and Oshtemo (coarse-loamy, mixed, active, mesic Typic Hapludalfs), 2 to 4% slope, developed on glacial outwash (Crum and Collins, 1995).

Agronomic Methods

Both treatments followed an 8-yr-old stand of alfalfa (established in 1996) and consisted of two 3-yr organic transitional rotation systems. In both systems, Year 4, which was corn, constituted the initial organic certification year. The more complex, annual crop transitional rotation was C-S-W/A-C, which incorporated dairy manure, cover crops, and interseeded crops. The second, more simple, perennial based transitional rotation consisted of conventional corn followed by 2 yr of continuous alfalfa (no manure or cover crops), followed by corn (C-A-A-C). Less reliance on tillage was one of the chief reasons the less complicated perennial alfalfa system was incorporated into this study. For Year 1 (2003), standing alfalfa was chisel plowed in May with 46-cm wide sweeps just below the crown in the (C-S-W/A-C) treatment, solid dairy manure was broadcast at a rate of 30 Mg ha^{-1} and incorporated into the soil along with the alfalfa, followed by a disk and soil finisher before planting corn at a rate of 69,000 seeds ha^{-1} in 76-cm rows for both treatments. Since the C-A-A-C was established conventionally, alfalfa was harvested for first cutting, followed by the same chisel plow with wide sweeps, disk, finisher, and 33.6 kg ha^{-1} N (as 28% ammonium nitrate) for a starter fertilizer before planting corn. Preemergence herbicides were used for weed control, followed by between row field cultivation (twice) and 84 kg ha^{-1} N (as 28% ammonium nitrate) side-dress fertilizer at last pass in early July. The side-dress treatment was the last prohibited substance (according to NOP standards) applied to either system (USDA, 2008a). The differences in establishment techniques between treatments (organic vs. conventional) were designed to test the effects of these transitional strategies on yield and soil quality. Yield measurements were taken at the end of the season using two methods, triplicate 1 m^2 quadrat hand-harvest and a two-row small plot (Massey Ferguson, Duluth, GA) combine harvester. Interseeded crops in the complex C-S-W/A-C treatment consisted of a red clover (*Trifolium pratense* L.) cover broadcast into Year 1 corn at a rate of 16.8 kg ha^{-1} after the last cultivation (early July), and alfalfa drilled into Year 3 winter wheat between the rows at a rate of 20 kg ha^{-1} in late April for added weed suppression and N building for subsequent corn. Including clover in the corn phase is a common organic management practice to provide weed competition and overwinter cover with subsequent organic matter incorporation, while providing a N-fixing legume in each year of the rotation. The C-S-W/A-C treatment was split in Year 3(2005) to investigate two separate wheat harvest methods. The C-S-W/A-C F treatment had wheat harvested as forage, while the C-S-W/A-C G treatment was harvested for grain. Field operations throughout the study were performed as indicated in Table 1.

Year 4 (2006) was the first certified organic season for both treatments. At this point, each of the two systems was managed identically. Standing alfalfa was chisel plowed in late April with 46-cm wide sweeps set at a depth just below the crown. This operation was followed by two diskings. Solid dairy manure was broadcast at a rate of 52 Mg ha^{-1} and incorporated along with the alfalfa twice with a soil finisher, before planting corn. Blue River Organics 26K21 88 DTM certified organic seed was planted at a rate of 69,000 seeds ha^{-1} in 76-cm rows in early June. Weed management was performed mechanically with a rotary hoe (twice) at VE and V1 growth stage and between row field cultivation (twice) at V2 and V3 stage of corn development (McWilliams et al., 1999). Yield measurements were taken with a two-row small plot (Massey Ferguson, Duluth, GA) combine from a central strip within each plot.

Table 1. Field management procedures by system rotation (treatment) and year throughout the transitional period and into the first certified organic season.

Procedure	Corn–alfalfa–alfalfa–corn	Corn–soybean–wheat/alfalfa–corn forage	Corn–soybean–wheat/alfalfa–corn grain
		2003	
Mow/rake/bale	X		
Chisel plow	X	X	X
Manure		X	X
Disk	X	X	X
Soil finish	X	X	X
Starter N	X		
Plant corn	X	X	X
Herbicide	X		
Rotary hoe		X	X
Row cultivate	2X	2X	2X
Side-dress N	X		
Plant clover		X	X
Harvest corn	X	X	X
		2004	
Flail mow	3X		
Chisel plow	X	2X	2X
Soil finish	2X	2X	2X
Culti-pack	2X	X	X
Plant alfalfa	2X		
Plant soybean		X	X
Moldboard	X		
Disk	X		
Rotary hoe		3X	3X
Row cultivate		2X	2X
Manure		X	X
Harvest soy		X	X
Drill wheat		X	X
		2005	
Mow/rake/bale	2X	2X	
Plant alfalfa		2X	2X
Harvest wheat			X
		2006	
Chisel plow	X	X	X
Disk	2X	2X	2X
Manure	X	X	X
Soil finish	2X	2X	2X
Plant corn	X	X	X
Rotary hoe	2X	2X	2X
Row cultivate	2X	2X	2X
Harvest corn	X	X	X

Soil Quality Measurements

Six 40 mm diam. intact soil cores were taken in late April of 2004 and 2006 to a depth of 7 cm at three locations along a diagonal transect for each replicate plot. Bulk density was measured on three of the six cores as described by Elliott (1999). Aggregate size distribution was measured in triplicate 25-g subsamples of the remaining soil using a wet sieving apparatus similar to the Yoder (1936) model and designed to hold nested sieves. We incorporated a procedure described by Kemper (1965). Four aggregate size classes were collected from each treatment, replicate and subsample (core): >2000, 1000 to 2000, 53 to 1000, and <53 μm diam. Macroaggregates were defined as the >2000 and 1000 to 2000 μm diam. size fractions. Microaggregates were defined as the 53 to 1000 and <53μm diam. size fractions. Soils were air dried for a minimum of 48 h and the 25-g subsamples were placed on the top sieve of each nest. To slake the air-dried soil, the sieve nest was lowered into water just above the top sample for a period of 5 min before the start of the wet-sieving motion. Aggregate size classification and sieving method are typical of previous studies (Grandy and Robertson, 2006). The apparatus specifications of oscillation time (3 min), stroke length (4 cm), and frequency (45 cycles min^{-1}) were held constant.

Following wet sieving, material remaining on each sieve was backwashed into preweighed 250 mL glass beakers and dried at 60°C for 24 h. The dried aggregates retained from each size class were weighed and stored at room temperature. Floating organic matter (plant debris) was removed from the >2000 μm aggregate size class. Organic matter associated with other aggregate size classes was not removed from the final (sand-free) aggregate weight. Aggregates falling into the <53 μm diam. size class were discarded. The sand-free water stable aggregates were measured by adding 30 mL of 5 g L^{-1} sodium hexametaphosphate and shaking on an orbital shaker at 150 rpm for 24 h. The dispersed organic matter and sand was collected on a 53-μm mesh sieve, washed with deionized water, and dried at 60°C for 48 h; these weights were subtracted from the other sample weights to yield the sand-free portion of the samples.

Weed Seedbank Assessment

Weed seedbank sampling in each of the two (2005) and three (2006) systems was conducted in early spring each year before planting. Ten soil cores (2 cm diam. to a depth of 7 cm) were collected from three 25 by 25 cm quadrats along a diagonal transect within each plot. The 10 cores were composited for each of the three sampling locations. In this study, we used a modified sampling technique from three previous direct germination studies that showed direct relationships between the readily germinable fraction of the weed seedbank and the response of the aboveground weed community (Forcella, 1992; Menalled et al., 2001; Smith and Gross, 2006).

Soil samples were thinly spread (approximately 0.5 cm) over a 4 cm deep layer of soil-less seedling mix (Sun Gro Horticulture, Bellevue, WA) in 25 by 25 cm plastic greenhouse flats. Flats were randomized on benches in a temperature-controlled greenhouse and kept well watered under natural light from late April through late July in 2005 and mid-May through early November in 2006 (when flats of both 2005 and 2006 soil were monitored for emergence). Typical greenhouse temperatures ranged between 20 and 30°C. Emerging seedlings were monitored weekly at first, then, as fewer new seedlings emerged, at intervals of varying length. Seedlings were counted, identified, and removed from the flats. As seedling emergence ceased, the soil mix was stirred and rewatered until all emergence was exhausted.

A stationary position was chosen at random and used for repeated measures of in-field weed surface density on all plots. Digital images were taken from the stationary position using a tripod at the same height, in the same location above a 1 m^2 quadrat. Sampling interval frequency was one image per week for each plot from late April to late June during the 2005 growing season. Images were stored until the end of the growing season, then all images were analyzed for percentage of crop, soil, and weed surface densities by scanning 1000 points per image using Surfaces (SMA, 2005) software. Percent weed cover data was then compared to weed seedling germination data obtained from the greenhouse assays.

Weed species net primary production was estimated by annual maximum plant biomass accumulation or, in the case of cover crops, biomass just before incorporation (KBS-LTER, 2001). Plant biomass was measured by quantifying the peak dry mass of weeds per m^2 in each plot. Two or three random sampling locations in each plot were sampled for weed biomass. Before corn harvest (2003 and 2006), 1.5 by 0.65 m quadrats were oriented with the long side in a north/south direction. This direction was perpendicular to the crop rows and allowed for assessment of both the row and interrow plant communities. Before clover incorporation (C-S-W/A-C 2004), three random sampling locations in each plot were sampled for clover and weed biomass using a 0.5 by 2 m quadrat. Plant biomass was quantified by clipping all plants within the sampling area at ground level. Weed species were combined within subsamples for total above ground noncrop biomass (2003, 2004) and were separated by species in 2006 for weed species richness, dried at 60°C for 48 h and weighed.

Statistical Analysis

Yield comparisons between treatments for corn and forage cuttings were analyzed through ANOVA using the mixed procedure (PROC MIXED) in Statistical Analysis Software (SAS) version 9.1.3 (SP4) (SAS Institute, 2008), where treatments were considered as fixed effects with yield (Mg ha^{-1}) as the continuous response variable. Soil aggregate distribution and bulk density comparisons between treatments and years were analyzed by ANOVA (PROC MIXED) in SAS, where treatments were considered as fixed effects and percent soil aggregation within each size class as the continuous response variables between years, and bulk density as the continuous response variable within and between years. Weed seedbank emergence (density) and number of species (richness) comparisons between treatments and years were analyzed by ANOVA (PROC MIXED) in SAS. Treatments were considered as fixed effects with density and richness as the continuous response variables within and between years, and weed surface density as the continuous response variable within season and aboveground biomass as the continuous response variable within individual years. Mean separations were obtained by the Least Significant Difference (LSD) test and considered significantly different at $p < 0.05$. The Mixed Procedure was especially appropriate for this study since we had two or more variance components such as replicate, subsample, and years as random effects. The Mixed Procedure allowed data obtained through repeated measures of surface density and other measurements in the unbalanced design (our split-plot of one treatment but not the other) to be analyzed with a wider variety of correlation structures.

RESULTS AND DISCUSSION

Yields

Corn yields from the first transitional year (2003) showed no significant differences ($\alpha = 0.05$) between the C-S-W/A-C and C-A-A-C treatments (Table 2) and averaged 8.83 Mg ha^{-1}. Yields from both treatments were equal to or greater than local and regional averages for corn grown conventionally (USDA-NASS, 2003, 2006). We harvested alfalfa from the C-A-A-C treatment before planting corn (first cutting); and this yield averaged 3.52 Mg ha^{-1}. Standing alfalfa was tilled-in (preplant) to the C-S-W/A-C treatment in an amount approximately equal to that which was removed from the C-A-A-C treatment.

Table 2. Yield results by year, rotation (treatment), and crop throughout the transitional period and into the first certified organic season.

Year	Rotation†	Crop	Mg ha^{-1}
2003	C-A-A-C	alfalfa	3.52
		corn	8.93a‡
	C-S-W/A-C	corn	8.73a
2004	C-A-A-C	alfalfa	0.00
	C-S-W/A-C	soybean§	2.49
2005	C-A-A-C	alfalfa	
		first cutting	1.23b
		second cutting	0.87b
		total	2.10b
	C-S-W/A-C F	wheat/alfalfa	
		first cutting	4.03a
		second cutting	0.77b
		total	4.80a
	C-S-W/A-C G	wheat	2.41
2006	C-A-A-C	corn	6.66a
	C-S-W/A-C F	corn	6.73a
	C-S-W/A-C G	corn	6.98a

† C = corn, A = alfalfa, S = soybean, W = wheat, F = wheat harvested as forage, G = wheat harvested as grain.

‡ Mean values followed by the same letter within each year are not significantly different ($\alpha = 0.05$).

§ Actual yield based on same variety on separate study.

No acceptable yield was produced for either treatment during Year 2 (2004). Alfalfa establishment in the C-A-A-C treatment was poor in the spring due to extreme wet conditions; as a result, weeds were the dominant biomass. Efforts to mow weeds throughout the season failed to promote alfalfa growth and the crop was replanted in August. Soybean yield estimations were included in the yield results (Table 2) using data from a study conducted at the same research station during the same year using the same variety and similar rotational strategy (Mutch and Martin, 2005, p. 21). The soybean crop in this study did not fail as a result of climate or agronomic management practices; rather all four replications were browsed so heavily by deer (*Odocoileus virginianus*) as to not produce a viable yield.

During Year 3 (2005), the C-S-W/A-C treatment plots were split based on harvestable forage crops (see Methods). There were significant treatment differences between the first ($p < 0.01$) and second forage harvests for this treatment. Additionally, there was a difference in the amount of total forage produced between the two rotations in 2005 ($p < 0.05$) (see Table 2).

The fourth year (2006) was the first fully certified organic season and both treatments were managed identically. There were no significant grain yield differences ($\alpha = 0.05$) between any of the treatments (Table 2). Archer et al. (2007) investigated similar rotations to ours and reported average yields of corn, soybean, and wheat strikingly similar to those shown in our study for Years 2, 3, and 4; however in our study we show first-year corn yield on par with corn grown conventionally in the Archer study.

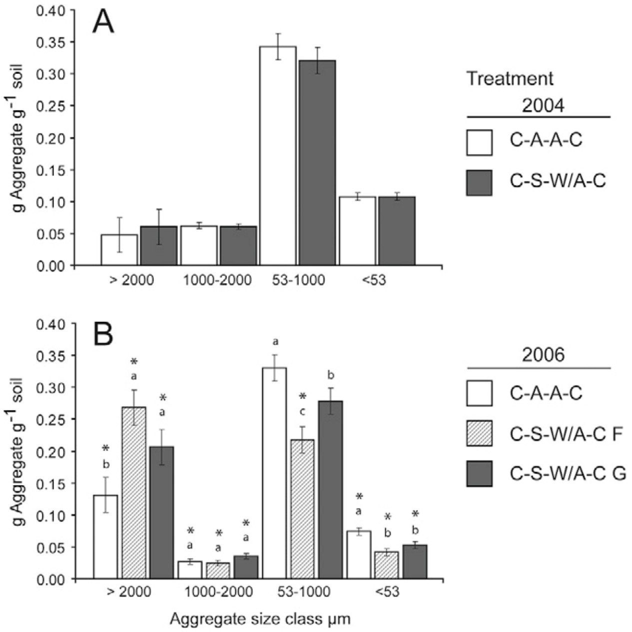

Fig. 1. Mean weight of soil aggregates at 0- to 7-cm depth distributed by aggregate size class and treatment for years (A) 2004 and (B) 2006. *Significant treatment differences within the same year at the 0.05 probability level. † Significant within treatment differences between years at the 0.05 probability level. Bar values are mean ± one standard error.

Soil Aggregate Size Distribution and Bulk Density

Rotation treatment had no effect on size distributions of soil aggregates from 0- to 7-cm depth ($\alpha = 0.05$) at the end of Year 1 of the transition period, 2004 (Fig. 1). However, by the conclusion of the study in 2006, our results indicate a substantial increase in the >2000 μm soil macroaggregate size class at the 0- to 7-cm depth for the C-S-W/A-C treatments, the treatments that included the incorporation of leguminous cover crops and solid dairy manure over a period of 3 yr. There was a 2.7- and 3.4-fold increase in aggregates of this size class for the C-A-A-C, C-S-W/A-C treatments, respectively. The C-S-W/A-C system generated a 4.5-fold increase in aggregates of this class when wheat interseeded with alfalfa was harvested as forage. While this effect on large soil macroaggregates may be temporary, as future agronomic management practices such as an increase in tillage operations may negate the effect, it reflects an important step in the right direction for soil quality during the transition to an organic production system. Both within season and annual increases in macroaggregates have been demonstrated (Bipfubusa et al., 2008; Yang et al., 2007; Perfect et al., 1990; Tisdall et al., 1978), but results vary widely depending on sampling and analysis methods (Ashman et al., 2003; Douglas and Goss, 1982; Marquez et al., 2004; Niewczas and Witkowska-Walczak, 2005; Watts et al., 1996). Long-term studies show results ranging from slight increases in macroaggregates with incorporated FYM (Blair et al., 2006; Holeplass et al., 2004; Rasool et al., 2007), to significant increases in aggregation of all size classes with incorporated FYM. This range of outcomes occurred with neither crop yield improvement nor any accompanying adverse effects on water quality (Edmeades, 2003).

The 2.7-fold increase in macroaggregates for the C-A-A-C treatment occurred without any incorporation of FYM (or cover crops) during the 3-yr transitional period. This may be attributable to the management practices performed during the 8 yr of continuous alfalfa and two seasons during the transition period. Both treatments were established after 8 yr of continuous alfalfa, however soil cores were collected in the spring of Year 2 (2004) after primary tillage had occurred the year before. Grandy and Robertson (2006) reported a substantial reduction in mean soil aggregate size and in the proportion of intraaggregate, physically protected organic matter after primary tillage of an untilled soil, while others have shown an increase in soil aggregation with reduced or no-till systems (Green et al., 2005; Mikha and Rice, 2004; Park and Smucker, 2005; Taboada-Castro et al., 2006; Zotarelli et al., 2007). Therefore, although the C-A-A-C treatment did not incorporate FYM, the immediate decrease in aggregate size and distribution we would expect with primary tillage, may have been followed by the slight increase in these properties after the system returned to the perennial alfalfa.

Increases in the >2000 μm macroaggregate size class at the 0- to 7-cm depth for these two systems were accompanied by a decrease in the 1000- to 2000-μm macroaggregate size class for both treatments (Fig. 1). There was a significant decrease in the 53- to 1000-μm microaggregate size class over the course of the transition period for the C-S-W/A-C treatments, but this aggregate size class was unchanged for the C-A-A-C treatment. There was a significant in the 53- to 1000-μm microaggregate size class between years for the C-S-W/A-C F treatment. Microaggregates in the <53 μm size class were identical between treatments in 2004, but showed a significant decline for all treatments in 2006. There were also significant treatment differences in this size class after the 3-yr transition period (Fig. 1).

Six et al. (1999) suggested that the faster turnover rate of macroaggregates in a more conventionally tilled system compared with a no-till system leads to a slower rate of microaggregate formation within macroaggregates and less stabilization of new SOM in free microaggregates under such a system. The benefits of incorporating green manure and FYM may have been destroyed by the higher amount of tillage in the C-S-W/A-C treatments for the lower diameter aggregate size classes.

Soil bulk density has been used as another indicator of soil quality (Werner, 1997; Karlen et al., 1994) and has been shown to decrease with the incorporation of organic amendments such as plant residue and FYM (Latif et al., 1992; Sharma and Gupta, 1998). Bulk density (0–7 cm) significantly declined between 2004 and 2006 for each of the rotation treatments which indicates an improvement associated with either rotation strategy.

Soil bulk density for the two treatments showed a significant difference ($p < 0.05$) after the first year of the transition period (2004), where the average bulk density was 1.28 and 1.37 g cm^{-3} for the C-A-A-C and C-S-W/A-C treatments, respectively (Fig. 2). This outcome is attributed to the higher number of passes with farm machinery necessitated by the annual crop rotation (C-S-W/A-C). While soil aggregate distribution and bulk density tend to be highly variable both spatially and temporally, our results indicate the more diverse crop rotation (C-S-W/A-C) showed significant increases in macroaggregates and a decrease in bulk density. We cannot ascertain, however, whether these improvements in soil quality characteristics were attributable to the diverse rotation or the combination of rotation with the addition of FYM.

Weed Seedbank Assessment

There was a significant effect caused by the transitional management strategy on seedbank density ($p < 0.05$) in 2005, the final transitional year; the C-A-A-C treatment had a lower seedbank density than the C-S-W/A-C treatment (Fig. 3A). Before the first certified organic season (2006), the seedbank densities of the C-A-A-C and the C-S-W/A-C G treatments changed relatively little. There was no significant effect of year on the C-A-A-C treatment. However, the seedbank in this treatment was significantly lower ($p < 0.01$) in weed density compared to the C-S-W/A-C G treatment. There was a significant effect caused by harvest management on the split treatment; C-S-W/A-C F had the highest level of seedbank density in 2006 compared with either of the other two management systems ($p < 0.001$; Fig. 3A).

Neither of the 3-yr transitional management strategies had an effect on weed species richness ($\alpha = 0.05$) until the end of the transition period. Before the first certified organic season (2006), both C-S-W/A-C treatments had significantly higher weed species richness than the C-A-A-C treatment ($p < 0.05$) (Fig. 3B). Seedbank samples were collected for both treatments in 2005 (before the wheat phase of the C-S-W/A-C rotation) and the following season (2006) before planting corn. Gross (1990) found that the direct germination technique, while requiring a substantial amount of time and space, offers a more comprehensive account of weed species present in the seedbank than does seed elutriation. Menalled et al. (2001) sampled soil in this manner to a depth of 15 cm (0–5- and 5–15-cm depths). Only data for the 5-cm depth was reported because of the tendency of agricultural weeds to germinate and emerge from the top few centimeters of soil (Buhler, 1995). Smith and Gross (2006) sampled soil in a similar pattern to a depth of 5 cm. They reported the germinable fraction of the weed seedbank experienced relatively rapid change in composition and abundance because significantly higher weed seedbank density and richness had occurred after the wheat phase of a similar rotation. Here, we saw a significant treatment effect on weed seedbank density before planting wheat, with a rapid increase in density and richness the year following the wheat phase.

The C-S-W/A-C treatment harvested as forage (2006) had significantly higher weed species richness than the same treatment the previous year ($p < 0.05$). There was no effect of year on weed species richness for the C-A-A-C treatment ($\alpha = 0.05$; Fig. 3B). Forage crops such as alfalfa have been used in herbicide-free rotations for their effects on the weed community through competition, mowing, and suppression of weed seed germination (Bellinder et al., 2004). The annual increase in weed species richness in the C-S-W/A-C treatment may be attributable to previous weed management practices or weed seed inputs to the soil via raw manure application or some combination of each. Since the persistence and dynamics of weed seedbanks varies with each crop in rotation (Smith and Gross 2006), we cannot determine from this study the source of recruitment.

Despite the significantly higher weed potential throughout the 2005 growing season as indicated by germination assays (Fig. 3A and 3B), the percent surface cover of weeds was significantly less ($p < 0.05$–0.001) in the more complicated C-S-W/A-C treatment compared with the C-A-A-C treatment until the former treatment was split into two separate harvest methods (Fig. 4). Once this treatment was split, the percent surface cover of weeds began to diverge to the point where the C-S-W/A-C treatment harvested as forage did not differ significantly from the C-A-A-C treatment ($\alpha = 0.05$), but was significantly higher in weed surface density than the C-S-W/A-C treatment harvested as grain ($p < 0.05$; Fig. 4). This demonstrates that particular transitional management strategies such as the more complicated C-S-W/A-C treatment can overcome an increase in weed seedbank (through seed rain, the incorporation of green manure and FYM) by maintaining

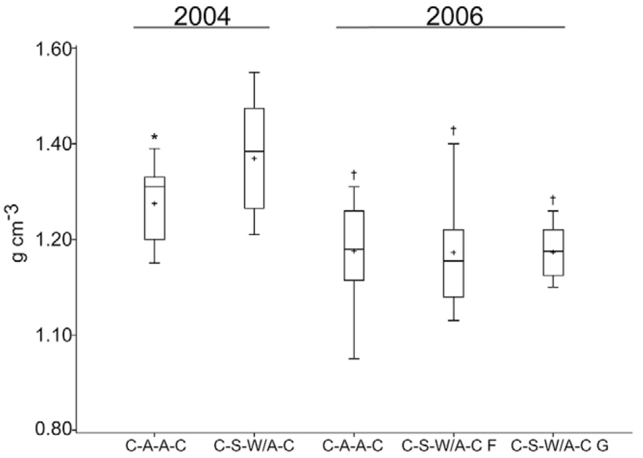

Fig. 2. Boxplots showing differences in soil bulk density (0–7-cm depth) between treatments and years. *Significant treatment difference within the same year $p < 0.05$. †Significant difference of the same treatment between years $p < 0.05$.

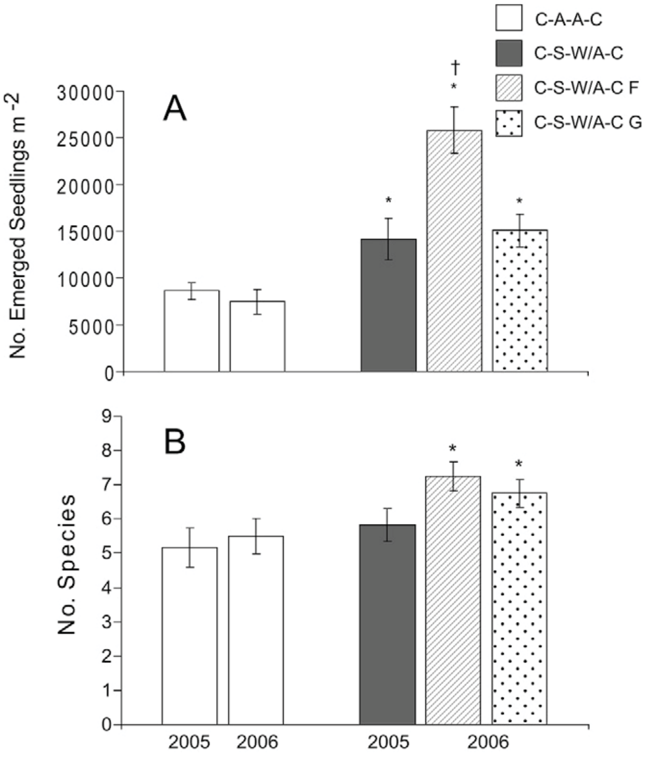

Fig. 3. Density (A) and species richness (B) of weed seedlings emerged from spring 2005 and 2006 soil seedbank samples. C = corn, A = alfalfa, S = soybean, W = wheat, F = wheat harvested as forage, G = wheat harvested as grain. Bar values are mean ± 1 SE for $n = 12$. *Significant treatment differences at the 0.05 probability level. †Significant split treatment difference at the 0.05 probability level.

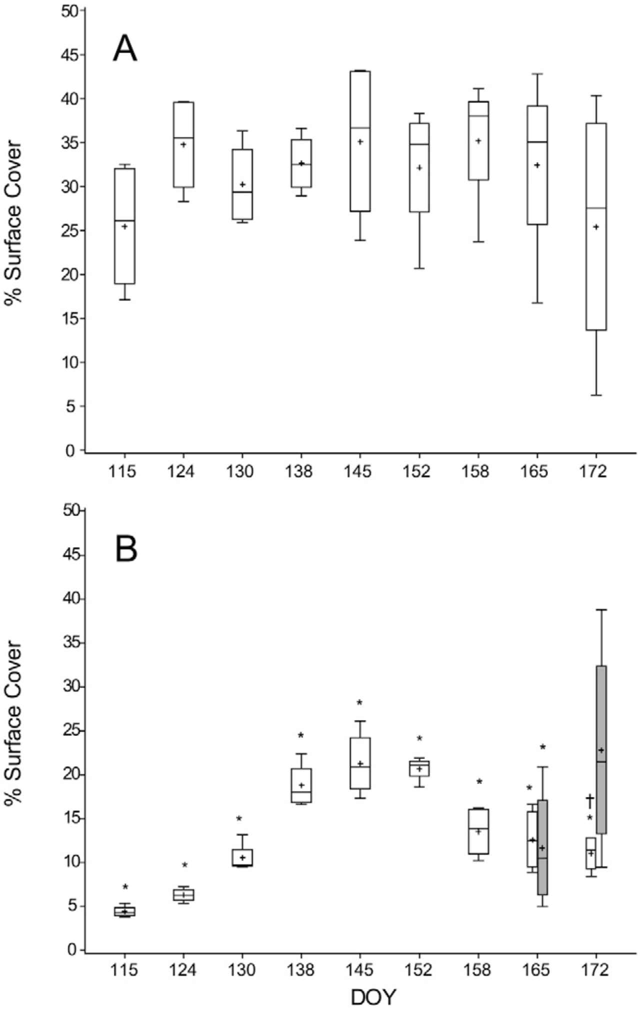

Fig. 4. Boxplots showing 2005 weed surface density for the (A) corn, alfalfa, alfalfa, corn (C-A-A-C) treatment and the (B) corn, soybean, wheat/alfalfa, corn (C-S-W/A-C) treatments. Shaded boxes represent the split from C-S-W/A-C where wheat was harvested as grain (open boxes) to wheat harvested with alfalfa as forage (shaded boxes). *Significant treatment differences on specific day of year at the 0.05 probability level. †Significant split treatment difference ($p < 0.05$).

companion or cover crops in a diverse rotation and performing disruptive mechanical practices such as rotary hoe and row cultivation during critical weed emergence periods. Weed biomass and density in the C-S-W/A-C treatments were equal to or considerably lower than in the C-A-A-C treatment irrespective of the significantly higher weed potential indicated by weed seedbank germination assays. The C-A-A-C treatment was also significantly higher ($p < 0.05$) in weed surface density at this point than that of the C-S-W/A-C treatment harvested as grain (Fig. 4A and 4B). We found no significant interaction between weed species in the germination assays and aboveground weed species biomass in the field (data not presented).

Fall aboveground weed biomass in the field did not differ significantly between treatments ($\alpha = 0.05$) after the first transitional management year (2003) when the harvested crop was corn (Fig. 5). Corn yield also did not differ significantly between treatments ($\alpha = 0.05$; Table 2) that year.

Spring aboveground weed biomass was significantly higher ($p < 0.05$) than red clover (cover crop) biomass at the start of the second transitional season (May 2004) before tillage in the C-S-W/A-C treatment (Fig. 6).

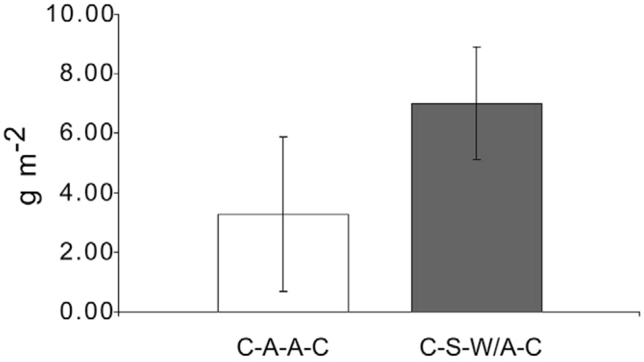

Fig. 5. Fall 2003 weed biomass by treatment. C = corn, A = alfalfa, S = soybean, W = wheat. Bar values are mean ± 1 SE.

Fig. 6. Spring 2004 cover crop (red clover) and weed biomass for the corn, soybean, wheat/alfalfa, corn (C-S-W/A-C) treatment. Bar values are mean ± 1 SE.

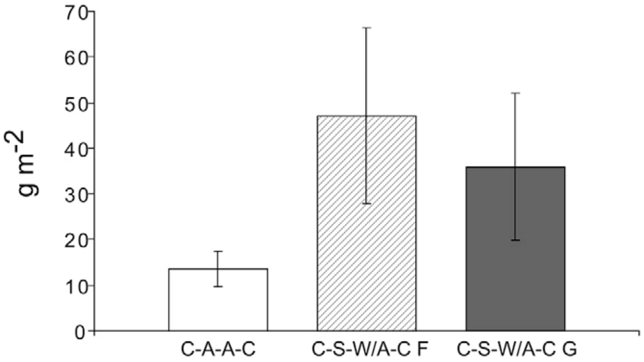

Fig. 7. Fall 2006 weed biomass by treatment. C = corn, A = alfalfa, S = soybean, W = wheat, F = wheat harvested as forage, G = wheat harvested as grain. Bar values are mean ± 1 SE.

Despite the significantly higher weed potential (Fig. 3A and 3B) for the more complicated C-S-W/A-C treatments throughout the 2006 growing season, there was no significant effect of transitional management strategy ($\alpha = 0.05$) on total weed biomass in the field at the end of the first certified organic season (fall 2006) when all transitional treatments were managed identically (Fig. 7). There was also no significant effect of transitional management strategy on corn yield ($\alpha = 0.05$; Table 2) that year. Interactions between weed management practices, weed populations, and crop yields are very complex. Initial weed densities and species composition interact with weed management strategies and weather patterns to generate weed seedbank responses in the field (Buhler, 1999). While the predictive value of weed seedbank estimations from soil remains questionable (Grundy, 2003; Menalled et al., 2001; Sjursen, 2001; Smith and Gross, 2006), in rotational systems where the seed bank is constantly being mixed, weed seedbanks can provide insights into cropping and management history as well as potential weed problems. By managing weed seedbanks through intensive focused practices, using a variety of strategies such as tillage, crop rotation, cover crops and mulches, established weed populations can diminish over time (Swanton and Booth, 2004). The role of soil disturbance in the promotion of weed recruitment via seed rain in the C-S-W/A-C treatments and the aboveground harvest regime of the C-A-A-C rotation likely accounted for the differences in weed species density emerged from the germination assays.

Climatic conditions most certainly had an effect on weed populations in this study. The extreme wet conditions that prevented proper establishment of alfalfa in the C-A-A-C treatment early in 2004, followed by drought conditions during the 2005 growing season, probably accounted for the differences between treatments found in the weed surface density estimations. Weed surface density estimations in the field during the 2004 and 2005 seasons were not indicative of the aboveground weed biomass measured during the final (2006) corn harvest (Fig. 4 and 7).

CONCLUSIONS

The more complex C-S-W/A-C rotation resulted in significantly more macroaggregates (>2000 μm) than the C-A-A-C strategy. However, even though each rotation resulted in significantly lower bulk density at the end of the transition period relative to Year 1, overall there were no differences in soil bulk density observed between the complex annual based and the perennial based transitional rotations. Additionally, the more complex C-S-W/A-C treatment, despite an increase in weed potential, decreased the weed seed bank responses compared with the simpler perennial based C-A-A-C treatment during the 3-yr transition to a certified organic system.

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