Agriculture, Ecosystems and Environment 189 (2014) 119–126

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Multivariate relationships influencing crop yields during the transition to organic management

M.E. Schipanski[a,b,*], R.G. Smith[c], T.L. Pisani Gareau[d], R. Jabbour[e], D.B. Lewis[f], M.E. Barbercheck[g], D.A. Mortensen[a], J.P. Kaye[b]

[a] Dept of Plant Science, The Pennsylvania State University, University Park, PA, USA
[b] Dept of Ecosystem Science and Management, The Pennsylvania State University, University Park, PA, USA
[c] Dept of Natural Resources and the Environment, University of New Hampshire, Durham, NH, USA
[d] Dept of Earth and Environmental Sciences, Boston College, Chestnut Hill, MA, USA
[e] Dept of Plant, Soil, and Environmental Sciences, University of Maine, Orono, ME, USA
[f] Dept of Integrative Biology, University of South Florida, Tampa, FL, USA
[g] Dept of Entomology, The Pennsylvania State University, University Park, PA, USA

ARTICLE INFO

Article history:
Received 12 October 2013
Received in revised form 19 February 2014
Accepted 20 March 2014
Available online 12 April 2014

Keywords:
Cropping system
Structural equation modeling
Cover crop
Tillage
Weed dynamics
Soil quality
Beneficial arthropods

ABSTRACT

Crop yields are influenced by multiple, interacting factors, making it challenging to determine how specific management practices and crop rotations affect agroecosystem productivity. This is especially true in cropping systems experiments in which multiple management practices differ between experimental cropping system treatments. We conducted a cropping systems experiment in central Pennsylvania, USA, to analyze the effects of initial cover crop and tillage intensity on feed grain and forage crop productivity during the transition to organic production. We hypothesized that treatment effects of (1) tillage intensity (full or reduced); and (2) initial cover crops (annual rye (*Secale cereale*) or timothy/clover (*Phleum pratense/Trifolium pratense*)) on grain crop yield in a 3-year cover crop/soybean (*Glycine max*)/corn (*Zea mays*) rotation would be mediated by key agroecosystem function indicators (soil quality, weed pressure, and predatory arthropod activity). We used structural equation modeling (SEM) to attribute yield variation to treatment effects and abiotic factors as mediated by these ecosystem functions. We found that tillage intensity had both direct and indirect effects on corn yields. Full tillage had a direct, positive effect on corn yields, a negative effect on perennial weed density, and negative effect on a soil quality indicator (labile soil carbon). Full tillage also had an indirect effect on corn yields as mediated by perennial weed density. The initial cover crop influenced predatory arthropod activity-density and perennial weeds in year 2 (soybean phase), but had no effects in year 3 (corn phase). Abiotic and site factors influenced crop yields and other ecosystem functions in both rotation years. Our results highlight the utility of analytical approaches that consider the relationships among agroecosystem components. Through the analysis of management effects on multiple ecosystem functions, our results indicate that managing weed populations through tillage in organic systems can have the strongest effect on crop yields, although short-term profit gains may be at the expense of long-term loss in soil quality and beneficial insect conservation.

1. Introduction

Agricultural management practices influence a suite of interacting ecosystem functions, including food production, nutrient cycling, water retention, and pest regulation. In addition, farmers rarely change single management practices, but rather combine multiple management practices into management systems, such as no-till or organic production systems. Cropping systems studies in which multiple practices differ between experimental cropping system treatments have contributed to our understanding of how management systems influence agroecosystem productivity and environmental impacts (Drinkwater, 2002). However, results from systems-based studies have primarily been evaluated using statistical approaches that separately analyze management effects on individual functions, such as soil quality, nutrient cycling, weed dynamics, and productivity (e.g., Drinkwater et al., 1998; Fortuna et al., 2003; Davis et al., 2005; Grandy et al., 2006).

* Corresponding author at: Department of Soil and Crop Sciences, Colorado State University, 1170 Campus Delivery, Fort Collins, CO 80521, USA.
Tel.: +1 970 631 7290; fax: +1 970 631 491 0564.
E-mail address: meagan.schipanski@colostate.edu (M.E. Schipanski).

http://dx.doi.org/10.1016/j.agee.2014.03.037
0167-8809/

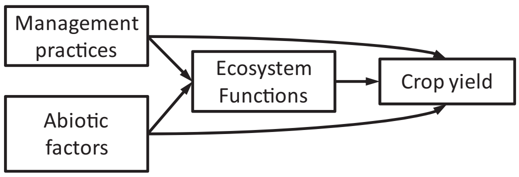

Fig. 1. Conceptual framework illustrating how management practices and abiotic factors can influence crop yield directly and indirectly through effects on mediating ecosystem functions.

More recently, the multifunctionality of cropping systems has been analyzed using multivariate statistical methods, including multiple regression (Cavigelli et al., 2008), principal components analysis (Clark et al., 1999), and discriminant analysis (Gosme et al., 2012). In addition, system multifunctionality has been represented visually using radar plots (Mäder et al., 2002) and the cumulative effects of management systems on multiple response variables have been evaluated through the use of semi-quantitative sustainability indices (Castoldi and Bechini, 2010). We still lack an understanding, however, of how management practices influence the relationships among multiple ecosystem processes or functions within cropping systems (Robertson and Swinton, 2005). For example, management practices and abiotic factors may influence crop yields directly or indirectly via mediating ecosystem functions, the ecological processes regulating the flux of materials and energy (Fig. 1). Understanding how ecosystem functions interact is particularly important for elucidating the mechanisms behind observed emergent effects of management practices. For example, shifting from a continuous corn rotation to a corn-soybean rotation improves nitrogen (N) availability to the succeeding corn crop that exceeds estimates of N inputs from soybeans (Karlen et al., 1991). This "rotation effect" is likely influenced by multiple interacting factors, including changes in labile soil carbon (C) inputs, microbial communities, and soil moisture dynamics (Gentry et al., 2013). Similarly, cover crops and tillage often have substantial impacts on weeds and crop yields (Liebman and Davis, 2000; Teasdale et al., 2007), but some of the underlying mechanisms remain unclear.

Structural equation modeling (SEM) is well-suited to analyze the structure of multivariate relationships that lead to the emergent properties of cropping systems (Grace, 2006). SEM allows researchers to propose an *a priori* model of structural relationships that include direct and indirect causal pathways. It is similar to a least-squares regression approach and has a history of use in the fields of biology, economics, psychology and sociology (Grace, 2006). More recently, SEM has been applied to studies in ecology (e.g., Grace et al., 2010; Sutton-Grier et al., 2010) and, to a lesser extent, agronomy (e.g., Davis and Raghu, 2010; Lamb et al., 2011), to test whether experimental data fit our conceptual models of ecosystem structure developed through prior experience and knowledge.

Managing tillage intensity to balance soil quality and pest control goals in organic production systems can be challenging. Building or maintaining soil organic matter is a cornerstone of organic production systems (Gliessman, 2007) due to the effects of organic matter on multiple functions, including nutrient cycling and pest and disease regulation (Zehnder et al., 2007; Drinkwater et al., 2008). Examples of management practices that can increase soil organic matter (SOM) include the use of cover crops, application of compost and manure, or reduction of tillage (Kuo et al., 1997; Drinkwater et al., 1998; Franzluebbers, 1999). However, weed management in organic systems typically relies on deep and/or frequent tillage and cultivation that depletes soil organic matter and has negative impacts on soil quality (Franzluebbers, 1999; Grandy and Robertson, 2007). In addition, tillage and the lack of living plant cover following tillage can have negative impacts on soil-dwelling predatory insect communities important for pest regulation in organic systems (Zehnder et al., 2007; Landis et al., 2000; Jonsson et al., 2008).

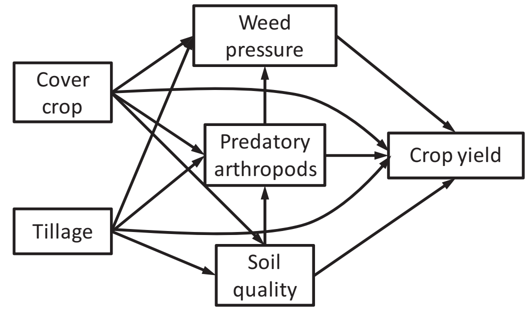

Fig. 2. Initial hypothesized model of how cover crop and tillage practices may affect crop productivity directly and indirectly through effects on soil quality, weed dynamics, and soil-dwelling predatory arthropod community dynamics.

The use of cover crops is another key component of organic production systems. Cover crops may help mitigate the negative effects of tillage in organic cropping systems by building soil organic matter, providing habitat for beneficial insects and suppressing weeds. Cover crops can provide important overwintering habitat for predatory arthropods, thereby promoting biocontrol of pest arthropods and increased weed seed predation (Gallandt et al., 2005; Lundgren and Fergen, 2011). Cover crop species differ in the functions they provide, such as pest control, erosion protection, and nutrient management. For example, annual cover crop species tend to have faster growth rates than perennials (Garnier, 1992), which can contribute to improved weed suppression. Perennial crop species tend to have a higher root:shoot ratios and root biomass is a key contributor to SOM stabilization and retention (Glover et al., 2010).

We conducted a cropping systems experiment to analyze the effects of initial cover crop and tillage intensity on soil quality, weed dynamics, and crop yields during the transition to organic production in a feed and forage production system in central Pennsylvania, USA. We focused on the transition period from conventional production to organic certification because the potential for reduced crop yields during this 3-year period is a constraint to the adoption of organic production practices (Pimentel et al., 2005). We hypothesized management practice effects on yield would be mediated by soil quality, weed populations, and predatory arthropods (Fig. 2). We used SEM to attribute yield variation to treatment effects as mediated by these three drivers of ecosystem function.

Some of the paths in our hypothesized model (Fig. 2) have extensive support in the existing literature, such as the effects of tillage on weed populations and the effects of weed populations on crop yields (Mirsky et al., 2012). Other relationships, however, are less well understood either because they have received little attention or they are thought not to be as important relative to other drivers. For example, tillage and cover crops can influence predatory arthropods, but there are few studies that examine how predatory arthropod activity-density directly influences crop yields (Letourneau and Bothwell, 2008; Letourneau et al., 2009). Complex trophic interactions may connect management effects on labile soil C to decomposer communities and predatory arthropod food webs that can influence weed seed predation and herbivore pressure on weeds and crops (Halaj and Wise, 2001). In addition, while it is widely assumed that organic matter quality and quantity affects crop yields, it is difficult to determine the importance of soil organic matter relative to other factors (Cassman, 1999). Our goal was to understand the relative importance of these different potential direct and indirect drivers of ecosystem functions within a cropping system and to identify potential management practices that could mitigate yield reductions during the transition period while maintaining or improving other key ecosystem functions.

2. Methods

2.1. Field site

Field experiments were conducted at the Russell E. Larson Agricultural Research Center near Rock Springs, PA (40°43′N, 77°55′W, 350 m elevation). The climate of central Pennsylvania is continental with 975 mm mean annual precipitation and mean monthly temperatures ranging from 3 °C (January) to 22 °C (July). The dominant soil type at this location is a Hagerstown silt loam (fine, mixed, semiactive, mesic Typic Hapludalf). Soil texture in our experimental field was predominantly clay loam with spatial variability in silt (range of 39.9–54.7%) and sand (14.0–27.0%) content across the field. Previous to the establishment of the study, the site had been in a conventional processing tomato (*Lycopersicon esculentum* Mill.) – winter wheat (*Triticum aestivum*) crop rotation using conventional tillage and processing tomato had been planted at the site the year before the initiation of the transition treatments.

2.2. Management and experimental treatments

The field experiment was established twice, first in the fall of 2003, and again in fall of 2004 in an adjacent field (the two experiments are hereafter referred to as Start 1 (S1) and Start 2 (S2)), in a split-plot, randomized complete block design with four replicates per treatment. To ensure relevance to organic feed grain cropping systems typical of the mid-Atlantic region, we relied on an advisory board composed of local organic farmers and agriculture professionals to guide the crop sequence and management decisions throughout the experiment. The 3-year crop sequence in the experiment consisted of a cover crop in the first year that was managed as a forage crop, followed by soybean in the second year, and corn in the final year. All management practices followed USDA National Organic Program guidelines (www.ams.usda.gov/NOP).

The main plot treatment was tillage system, and included moldboard plow (full tillage, FT) and chisel plow (reduced tillage, RT). The split-plot treatment was a perennial forage or a cereal grain cover crop planted in the first year of the 3-year rotation. Each subplot was 0.067 ha in size (24 m × 27 m). For a timeline and detailed description of all field operations, see Smith et al. (2011). Briefly, the cover crop treatments were initiated in fall 2003 in S1 and managed through the spring and summer 2004 (Fig. 3). The two cover crop treatments were rye (*Secale cereal* L.) with hairy vetch (*Vicia villosa* Roth) and timothy (*Phleum pratense* L.) with red clover (*Trifolium pratense* L.). The rye/vetch treatment (Rye) was managed as an annual grain crop, while the timothy/clover treatment (Tim) was managed as a sod-forming perennial forage. These crops were chosen because they are potentially capable of providing the benefits of “traditional” cover crops (e.g., improved soil quality, erosion control, weed suppression), as well as immediate financial returns if harvested for grain or forage during the transition period. In S1, Rye was harvested on 29 July 2004 for grain yield and 3 Aug. 2004 for straw yield. Timothy/clover was harvested twice for forage (2 Aug. and 14 Oct. 2004). Cover crops in S1 and S2 were managed in a similar fashion, but treatments were off-set in time by 1 year in S2 relative to S1. The site of S2 was planted with timothy, oat, and red clover cover crops for the year prior to the start of the second experiment.

Tillage in S1 first occurred following the rye harvest in September of rotation year 1 (Fig. 3). In the spring of rotation year 2, the Rye treatment was killed either by moldboard plow (FT treatment) or mechanical roller-crimper (RT treatment). The Tim treatment was tilled in the spring of rotation year 2. Through the remainder of the experiment, primary tillage in the FT system was accomplished with a moldboard plow in contrast to the chisel plow used in the RT system. Feed-grade soybean (late Group III maturity, ‘Pioneer 93B87′) was planted in all cover crop/tillage treatments in rotation year 2 at a row spacing of 76 cm. In rotation year 3, corn (‘Pioneer 36B08′) was planted at a row spacing of 76 cm. Rotary hoe and cultivator use was the same in both tillage treatments and their use was timed to control weeds germinating and emerging with the soybean and corn crops.

Fertility management during the experiment involved surface application of dairy manure and lime in 2003 across the entire experimental site at rates of 4480 kg ha^{-1} and 1120 kg ha^{-1}, respectively. Compost (from a feedstock of grass clippings, leaves, and food waste) was applied to all plots in August 2004 (S1) and September 2005 (S2) at a rate of 17,920 kg ha^{-1}. Bull pen manure was applied in March 2006 at a rate of 46 MT ha^{-1} (S1) and March 2007 at a rate of 32 MT ha^{-1} (S2).

In general, the same management practices implemented in S1 were implemented 1 year later in S2; however, there were minor deviations (Fig. 3). When the experiment began in S2 in fall 2004, plots to be planted to the Rye treatment were moldboard plowed before planting. Plots receiving the Tim treatment were mowed, but not plowed. Also, an additional cultivation occurred in corn in S2 in the reduced tillage system to improve perennial weed control.

Previous analyses informed our selection of variables representing weed, insect, and soil quality functions to include in our structural equation model. Specifically, previous analyses showed increased annual and perennial weed density and reduced corn yields in reduced tillage systems (Smith et al., 2011), management system effects on average annual predator activity-density (Jabbour, 2009), and reduced labile soil C in full tillage systems (Lewis et al., 2011). The methods used to quantify these variables are described below.

2.3. Soil analysis

We sampled soils four times in each rotation year: May, June-July, August, and September-October. On each sampling occasion, three composite soil samples were collected from random locations within each plot. Each sample comprised 15 individual soil cores (2.5 cm diameter × 15.2 cm depth). Labile C was analyzed on samples from each of the 12 collection dates. These data were previously published in Lewis et al. (2011), and the full soil analysis methods are described there. Briefly, we define labile C as organic C oxidized by a permanganate solution (Weil et al., 2003). For each sample, we combined 5 g of air-dried, sieved (2 mm) soil with 20 ml of 0.02 M permanganate solution in a polycarbonate tube. The permanganate solution contained 0.2 M potassium permanganate ($KMnO_4$) and 1 M calcium chloride ($CaCl_2$), and was adjusted to a pH > 7.2 using sodium hydroxide (NaOH). Samples were shaken for 2 min and then allowed to settle for 10 min. Next, 0.2 ml of supernatant from this slurry was added to 9.8 ml of deionized water, and this solution was briefly shaken by hand. The consequent reduction of permanganate was estimated with a Milton Roy Spectronic 21 D spectrophotometer at 550 nm. We assumed 9 mol of organic C were oxidized for every 1 mol of permanganate reduced.

2.4. Weed analysis

As described in Smith et al. (2011), weed densities were assessed by identifying weed species and counting all weeds present in five quadrats (0.25 m^2) randomly placed in each subplot. Weed density measurements were made before each disturbance event (i.e., cultivation), if multiple disturbance events occurred within a growing season. Weed density data were summed by species to determine

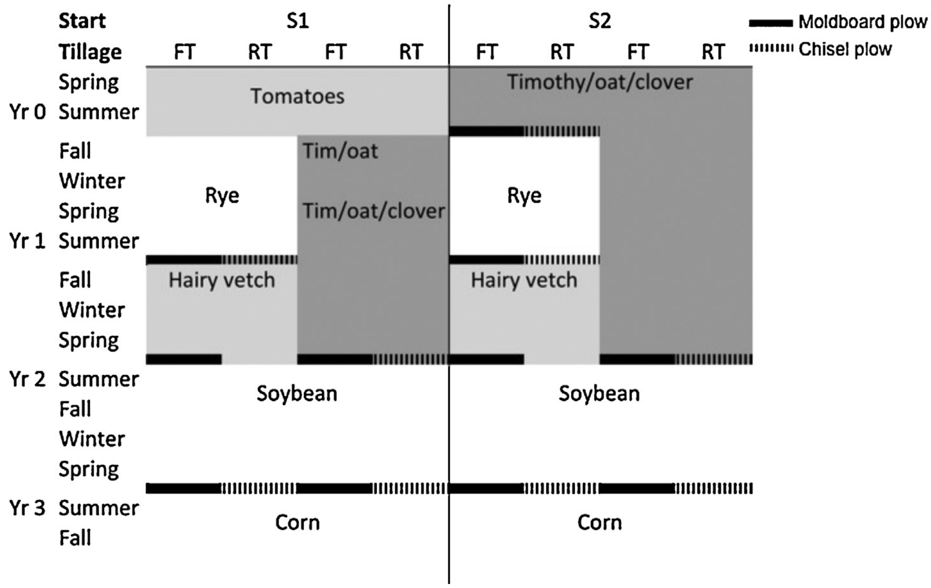

Fig. 3. Crop rotations and tillage management for both experimental starts (S1 and S2) from initiation year (Year 0) through Year 3. FT, full tillage; RT, reduced tillage.

the cumulative weed density in each quadrat and then averaged for each subplot for each growing season. For the SEM analyses, only perennial weed species were included for two primary reasons. Relative to annual weeds, perennial weeds were more consistently sensitive to tillage systems across rotation years 2 and 3, and less sensitive to differences in experimental start (Smith et al., 2011). In addition, perennial weeds can be more difficult to manage in organic and reduced tillage systems than annual weeds (Bond and Grundy, 2001).

2.5. Predatory arthropod analysis

We used a pitfall sampling method to assess the activity-density of ground-dwelling arthropods (Morrill, 1975). Pitfall sampling was done by burying 32-oz plastic containers flush with the soil surface. Each pitfall trap consisted of an inner sampling cup (87 mm diameter) filled with ethylene glycol (40 ml) and a funnel to exclude larger organisms. Three pitfall traps were randomly placed in each plot, opened for 72 h, and then the contents were collected and processed in the lab. In S1 and S2, we collected samples three times during the first and second rotation years (June, July or August, and October) and two times during the third rotation year (July and November).

Arthropod data from pitfall traps were averaged across sample dates for each experimental start and rotation year and recorded as activity-density (no. individuals/3 traps/72 h) for each taxon. The full list of arthropod taxa identified from pitfall samples is described in Jabbour (2009). For this analysis we focused on predator groups (Carabidae, Staphylinidae, non-bee Hymenoptera, Gryllidae, Araneae, and Opiliones).

2.6. Yields

We assessed crop yields over the 3-year duration of each experiment. Here we include only the cash crop yields (soybean and corn) in rotation years 2 and 3 because management systems were in different cover crop treatments in year 1. Soybean yields were assessed by hand-harvesting three subsamples from each subplot. Each subsample consisted of a 3 m (10 ft) section of a randomly selected row. Corn yields were assessed with a plot combine from each subplot.

2.7. Data analysis

We used SEM to analyze the impacts of tillage and cover crop systems on labile carbon, weed density, and predatory arthropod activity-density and their relative impacts on soybean and corn yields in rotation years 2 and 3, respectively. Fig. 2 illustrates the starting model informed by our hypotheses. Experimental start was also included as a third exogenous variable along with cover crop and tillage management systems to account for both site-to-site and year-to-year variability. Despite the two experimental sites being directly adjacent to one another and had similar soil types and biotic communities, initial soil conditions differed between the two sites (Lewis et al., 2011). In addition, initial cover crop management differed between S1 and S2 and may contribute to 'start' effects. Average values by experimental start and cropping system used in statistical models are presented in Table 1. We assessed the distribution of each variable and perennial weed density and predatory arthropod activity-density were log transformed to fit a normal distribution.

SEM uses a covariance matrix to test whether experimental data fit a proposed model (Kline, 1998). Chi-square test results indicate whether the model adequately fits the data (a non-significant Chi-square test indicates that the model fits the data; Grace, 2006). Path coefficients are calculated for relationships between variables and indicate the strength and directionality (positive or negative) of the relationship. When a response variable is connected to only one explanatory variable, path coefficients represent a standard regression coefficient. When response variables are connected to multiple explanatory variables, variance is partitioned among the explanatory variables and path coefficients represent standardized partial regression coefficients (Kline, 1998). Because of this variance partitioning, removal of a path between two variables can impact path coefficients between other variables. We used a sequential, hierarchical process of removing non-significant paths based on path coefficient *P*-values. In SEM, categorical exogenous variables (e.g., tillage and cover crop treatments and experimental start) are treated the same as in standard regression. For interpretation of path coefficients, a positive path coefficient for cover crop reflects a positive effect of rye relative to timothy/clover; a positive path coefficient for tillage reflects a positive effect of full tillage relative to reduced tillage; and a positive path coefficient for start reflects a positive effect of

Table 1
Summary of system average values for variables used in SEM models for rotation year 2 (soybean) and 3 (corn). Standard errors are in parentheses ($n = 4$).

Rotation year	Crop	Start[a]	System[b]	Labile C (mg/kg soil)[c]	Perennial weed density (#/m^2)[d]	Predatory arthropod activity-density[e]	Yield (kg/ha)[d]
2	Soybean	S1	Rye_full	337 (15)	2.2 (2.2)	12.4 (2.4)	1379 (255)
2	Soybean	S1	Tim_full	335 (9)	6.8 (1.9)	8.5 (1.2)	1237 (36)
2	Soybean	S1	Rye_red	385 (3)	2.0 (0.8)	13.6 (1.7)	1756 (31)
2	Soybean	S1	Tim_red	404 (20)	11.0 (3.9)	13.1 (1.5)	1142 (71)
2	Soybean	S2	Rye_full	389 (16)	2.8 (0.8)	15.9 (2.4)	3591 (348)
2	Soybean	S2	Tim_full	387 (13)	2.6 (0.6)	13.6 (0.9)	3945 (475)
2	Soybean	S2	Rye_red	402 (24)	17.0 (4.9)	26.3 (8.4)	2538 (174)
2	Soybean	S2	Tim_red	404 (18)	12.8 (3.1)	17.4 (2.3)	3497 (249)
3	Corn	S1	Rye_full	349 (13)	5.6 (2.6)	27.7 (2.8)	9414 (308)
3	Corn	S1	Tim_full	347 (5)	5.4 (2.0)	23.5 (1.8)	9325 (444)
3	Corn	S1	Rye_red	410 (2)	17.6 (5.3)	23.1 (1.7)	5861 (657)
3	Corn	S1	Tim_red	417 (10)	25.0 (4.8)	32.9 (4.5)	5950 (966)
3	Corn	S2	Rye_full	391 (18)	5.8 (1.7)	13.0 (0.8)	9414 (533)
3	Corn	S2	Tim_full	390 (6)	3.6 (1.0)	12.3 (1.0)	9947 (632)
3	Corn	S2	Rye_red	414 (13)	21 (12.2)	15.5 (2.0)	8792 (1190)
3	Corn	S2	Tim_red	406 (17)	6.2 (3.1)	13.5 (1.6)	8970 (671)

[a] S1, first experiment; S2, second experiment.
[b] Initial cover crop: rye, Rye; timothy–red clover, Tim; tillage: full tillage, full; reduced tillage, red.
[c] Adapted from Lewis et al. (2011).
[d] Adapted from Smith et al. (2011).
[e] Adapted from Jabbour (2009).

S2 relative to S1. Multiple squared correlations represent the percent of variance of a response variable explained by the model. All SEM analyses were conducted using AMOS version 5.0.1 (AMOS Development Corp., Spring House, PA).

3. Results and discussion

The two management tactics in this experiment, tillage intensity and initial cover crop, had direct effects on ecosystem function indicators of weed pressure, predatory arthropods, and soil quality as hypothesized (Figs. 1 and 2). However, these management effects did not translate to soybean yields as hypothesized. The best-fit model for the soybean rotation year indicated that full tillage had direct, negative effects on labile soil C and predatory arthropod activity-density (Fig. 4). Cover crop and tillage systems influenced perennial weed density directly and indirectly through a complex set of relationships. Perennial weed density was lower in Rye relative to Tim cover crop treatments. However, the Rye treatment also had a positive indirect effect on perennial weed density as mediated through a positive effect on predatory arthropod activity-density, which had a positive effect on perennial weed density (Fig. 4). Negative tillage effects on predatory arthropod activity-density mediated tillage effects on perennial weed density. The positive effect of predatory arthropods on perennial weed density may have been due to a suppression of herbivores (Crowder et al., 2010; Halaj and Wise, 2001). Trophic interactions within insect communities are complex, therefore, it is possible that predatory arthropods affected perennial weed density in other ways as well.

The initial (year 1) cover crop influenced perennial weed density and predatory arthropod activity-density in the subsequent year (year 2), but these effects did not persist into year 3 (Fig. 5). The negative effect of the initial rye/vetch cover crop on perennial

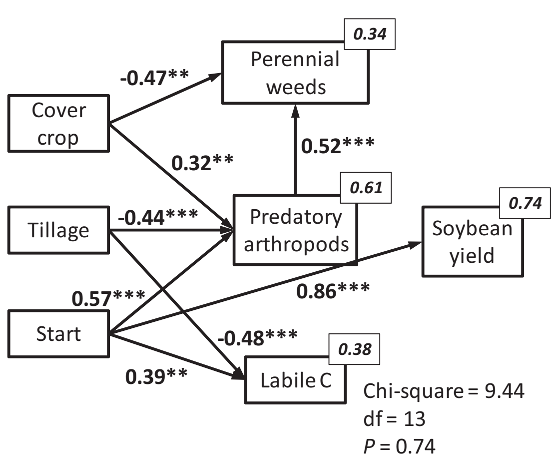

Fig. 4. Model results for rotation year 2 (soybean) showing standardized path coefficients along arrows, multiple square regression coefficients in boxes (R^2), and overall model fit (Chi-square test $P > 0.05$ indicates model and data structures do not differ). For categorical variables, a positive path coefficient for cover crop reflects a positive effect of rye relative to timothy/clover; a positive path coefficient for tillage reflects a positive effect of full tillage relative to reduced tillage; and a positive path coefficient for start reflects a positive effect of S2 relative to S1.
$^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$

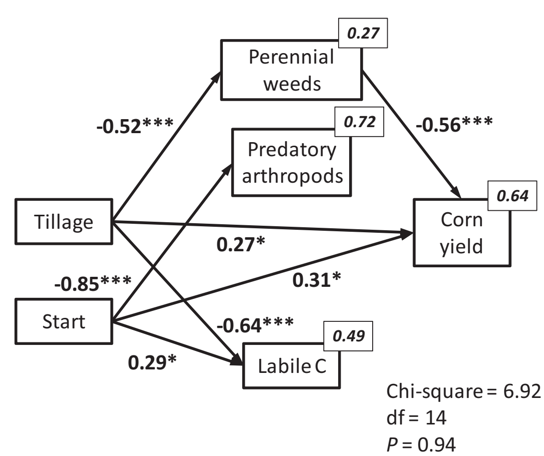

Fig. 5. Model results for rotation year 3 (corn) showing standardized path coefficients along arrows, multiple square regression coefficients in boxes (R^2), and overall model fit (Chi-square test $P > 0.05$ indicates model and data structures do not differ). For categorical variables, a positive path coefficient for cover crop reflects a positive effect of rye relative to timothy/clover; a positive path coefficient for tillage reflects a positive effect of full tillage relative to reduced tillage; and a positive path coefficient for start reflects a positive effect of S2 relative to S1. $^{*}P < 0.05$, $^{**}P < 0.01$, $^{***}P < 0.001$.

weed density in year 2 was likely due to the faster growth rate of the annual rye relative to the perennial timothy/clover cover crop. Rye is widely regarded as one of the more weed suppressive annual cover crops available due to its rapid growth under a wide range of conditions and potential allelopathic effects (Clark, 2007; Teasdale et al., 2012). In contrast to our findings where relative predator abundance was greater with an initial rye/vetch compared with timothy/clover cover crop, perennial leguminous cover crops increased predatory arthropod abundance relative to winter cereal cover crops in other studies (Davis et al., 2003; Gallandt et al., 2005).

Differences between experimental starts (a combination of abiotic and starting conditions) during the soybean year likely reduced our ability to detect management effects on soybean yields. Experimental start had direct effects on soybean yield and two ecosystem functions. The large differences in soybean yields between S1 and S2 (Table 1) were likely due to the influence of abiotic and corresponding management factors. Precipitation was 60% lower in 2005 than in 2006 during crop establishment (Smith et al., 2009). The initial soil conditions, including pH, available P, and labile soil C, also differed between S1 and S2 (Lewis et al., 2011) even though sites were directly adjacent to one another and had the same recent management history prior to the start of the experiment. The additional year of perennial Tim prior to the initiation of S2 (Fig. 3) may have contributed to the positive effect of S2 on labile soil C and predatory arthropod activity-density.

By the third year of the transition period (corn phase), experimental start effects were still important drivers of crop yield and other ecosystem functions. However, tillage intensity was also an important driver of corn yield both directly and indirectly while the initial (year 1) cover crop no longer influenced any of the ecosystem function indicators measured (Fig. 5). Full tillage systems had higher corn yields due to both direct effects and indirect effects mediated by perennial weed density. Combined, direct and indirect effects explained 64% of corn yield variability. Full tillage also had a negative effect on another ecosystem function indicator (labile C), but this did not translate into a yield effect. In rotation year 3, experimental start was the only factor that explained the variability in predatory arthropod activity-density. Start also influenced corn yields and labile soil C and both were greater in S2 than S1, similar to results from the soybean year.

The contrasting effects of tillage intensity on perennial weeds and labile soil C in year 3 highlight a major challenge in organic systems. Aggressive mechanical weed management has strong, positive effects on crop yields in the short term, primarily due to reduced weed pressure (Teasdale et al., 2007), but can result in soil quality degradation over the longer term (Grandy and Robertson, 2007). In particular, the type of tillage, in addition to the quantity of organic amendments that are applied, influences SOM levels. Chisel-plow based organic systems similar to our reduced tillage system had greater SOM compared to conventional no-till systems (Teasdale et al., 2007), while moldboard plow based organic systems had less SOM than no-till systems in other long-term studies (Grandy and Robertson, 2007). Perennial weeds, in particular, represent a challenge in organic cropping systems where synthetic herbicides are prohibited, because inversion tillage is one of the few effective management tools for reducing perennial weeds. Alternative strategies for controlling perennial weeds in organic systems include diversifying crop rotations to include several years of perennial forages that are mowed repeatedly and the use of rolled cover crops for weed control in no-till organic management systems (Bond and Grundy, 2001).

While labile soil C was sensitive to tillage intensity, it was not sensitive to cover crop treatments in either rotation year. The permanganate extraction method we used as an estimate of labile soil C can be more sensitive to tillage and crop rotation differences than other methods, including particulate organic C, microbial biomass C, and total organic C (Culman et al., 2012). Other measures, however, including particulate organic C and soil microbial community structure can be more sensitive to cover crop species effects in the short-term (Culman et al., 2012; Maul and Drinkwater, 2010) Cover crop effects on permanganate extractable soil C and soil quality likely occur at longer time scales than our study allowed (Kuo et al., 1997).

Our hypothesized model was the same for both soybean and corn crops, while the revised models based on our experimental data were distinctly different for each crop. Consistent relationships across both models suggest relationships that can be generalized across different crops and crop rotations, such as the negative effect of tillage on labile soil C. Relationships unique to each crop and rotation year combination, such as the effect of initial cover crop on perennial weeds in rotation year 2 or tillage effects on predatory arthropods during corn in rotation year 3, may be specific to either the crop or the rotation sequence used in this experiment. The shifting effects of tillage and initial cover crop management practices on ecosystem functions and crop yields during the 3-year rotation highlight the importance of evaluating management practices within a multi-year cropping systems context.

Through the application of SEM, we were able to quantify the relative effects of abiotic and site factors and management practices on crop yields and other ecosystem functions. SEM is a powerful tool for distilling significant relationships from a web of possible causal pathways among variables, including indirect and combined effects that might not otherwise be apparent when analyzing cropping system experiments. In our study, SEM confirmed indirect causal relationships among management practices and specific drivers of ecosystem functions that were not evident using standard statistical approaches focused on individual agroecosystem responses (e.g., Jabbour, 2009; Smith et al., 2011; Lewis et al., 2011). SEM can also provide guidance for future mechanistic research. For example, the mediating effects of predatory arthropods on perennial weed density in response to tillage and cover crop systems in the soybean year warrant additional research. SEM also has the capability to define conceptual variables (latent variables) using multiple indicator variables (Davis and Raghu, 2010). For example, soil quality is a concept that is influenced by multiple variables, such as soil C, aggregate stability, and water holding capacity, among others. However, the size of our dataset ($n = 32$) and our sampling design limited our ability to utilize latent variables.

Our hypothesized model (Fig. 2) was much more complex, containing more causal pathways, than our subsequent revised models (Figs. 4 and 5). Our relatively small dataset allowed us to detect the strongest relationships between variables, but likely limited our ability to detect more subtle relationships. For this study, we developed our SEM model based on our pre-experiment hypotheses. The power of SEM is greatest with larger datasets and when conceptual models are clearly defined during the planning stage of an experiment such that the data are collected in the appropriate time and space to solve for the paths in the conceptual model.

4. Conclusions

Each agricultural management system encompasses a suite of practices, including crop rotations. Therefore, when farmers adopt alternative management systems, such as transitioning from conventional to organic production, they are not merely changing one practice but rather multiple soil, crop, and pest management practices simultaneously. As a result, more agricultural research is being devoted to systems-level studies that more effectively capture the multivariate nature of agricultural management systems. However, while systems-based experiments may be more agronomically realistic, our approaches to analyzing these studies have typically relied on univariate procedures to analyze cropping system treatment effects on single response variables along disciplinary lines, such as effects on weeds or yields or soil quality. Univariate approaches are unable to account for the complex direct and indirect relationships between the suite of practices within a management system and other components of the agroecosystem that ultimately drive crop yields. Agronomists can look to other fields, such as sociology and ecology, which have a history of understanding complex systems for improved tools to analyze the multivariate relationships that occur within cropping systems experiments. SEM represents one such tool.

Through the application of SEM, we identified the structure of the relationships between mediating ecosystem functions and crop yields sensitive to cover crop and tillage practices. Our results suggest abiotic and site factors and tillage practices are strong drivers of yield variability during the transition period to organic management. In the short term, tillage practices can have both direct and indirect effects on crop yields via changes in perennial weed density. The initial cover crop and tillage practices used during the transition period can directly influence other key ecosystem functions, but these may not manifest in changes in crop yields in the short term.

Acknowledgements

We thank S. Harkcom, D. Heggenstaller, V. Houck, B. Jones, S. Kinneer, C. Mullen, C. Nardozzo, D. Sandy, and S. Smiles for technical assistance. We would also like to acknowledge the invaluable advice provided by our advisory board: C. Altemose, L. Garling, J. Moyer, B. Snyder, K. Yoder, P. Yoder, A. Ziegler, and L. Zuck. Funding for this research was provided by the USDA IREE Competitive Grants Program-IPM-ORG-112.E.

References

Bond, W., Grundy, A.C., 2001. Non-chemical weed management in organic farming systems. Weed Res. 41, 383–405.
Cassman, K.G., 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. Proc. Natl. Acad. Sci. USA 96, 5952–5959.
Castoldi, N., Bechini, L., 2010. Integrated sustainability assessment of cropping systems with agro-ecological and economic indicators in northern Italy. Eur. J. Agron. 32, 59–72.
Cavigelli, M.A., Teasdale, J.R., Conklin, A.E., 2008. Long-term agronomic performance of organic and conventional field crops in the Mid-Atlantic region. Agron. J. 100, 785.
Clark, A., 2007. Managing cover crops profitably. Sust. Ag. Network, USDA-SARE, Beltsville, MD.
Clark, M.S., Horwath, W.R., Shennan, C., Scow, K.M., Lantni, W.T., Ferris, H., 1999. Nitrogen, weeds and water as yield-limiting factors in conventional, low-input, and organic tomato systems. Agric. Ecosyst. Environ. 73, 257–270.
Crowder, D.W., Northfield, T.D., Strand, M.R., Snyder, W.E., 2010. Organic agriculture promotes evenness and natural pest control. Nature 466, 109–112.
Culman, S.W., Snapp, S.S., Schipanski, M.E., Freeman, M.A., Beniston, J., Drinkwater, L.E., et al., 2012. Permanganate oxidizable carbon reflects a processed soil fraction that is sensitive to management. Soil Sci. Soc. Am. J. 76, 494–504.
Davis, A., Renner, K., Gross, K., 2005. Weed seedbank and community shifts in a long-term cropping systems experiment. Weed Sci. 53, 296–306.
Davis, A.S., Dixon, P.M., Liebman, M., 2003. Cropping system effects on giant foxtail (*Setaria faberi*) demography: II. Retrospective perturbation analysis. Weed Sci. 51, 930–939.
Davis, A.S., Raghu, S., 2010. Weighing abiotic and biotic influences on weed seed predation. Weed Res. 50, 402–412.
Drinkwater, L., 2002. Cropping systems research: reconsidering agricultural experimental approaches. HortTech. 12.
Drinkwater, L.E., Wagoner, P., Schipanski, M., Snapp, S., Jackson, L.E., 2008. Ecologically-based nutrient management. In: Snapp, S., Pound, B. (Eds.), Agricultural Systems: Agroecology and Rural Innovation for Development. Academic Press, San Diego, CA.
Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262–265.
Fortuna, A., Harwood, R.R., Robertson, G.P., Fisk, J.W., Paul, E.A., 2003. Seasonal changes in nitrification potential associated with application of N fertilizer and compost in maize systems of southwest Michigan. Agric. Ecosyst. Environ. 97, 285–293.
Franzluebbers, A., 1999. Soil carbon, nitrogen, and aggregation in response to type and frequency of tillage. Soil Sci. Soc. Am. J. 63, 349–355.
Gallandt, E.R., Molloy, T., Lynch, R.P., Drummond, F.A., 2005. Effect of cover-cropping systems on invertebrate seed predation. Weed Sci. 53, 69–76.
Garnier, E., 1992. Growth analysis of congeneric annual and perennial grass species. J. Ecol. 80, 665–675.
Gentry, L.F., Ruffo, M.L., Below, F.E., 2013. Identifying factors controlling the continuous corn yield penalty. Agron. J. 105, 295–303.
Gliessman, S., 2007. Agroecology: The Ecology of Sustainable Food Systems. CRC Press, Boca Raton.
Glover, J.D., Culman, S.W., DuPont, S.T., Broussard, W., Young, L., Mangan, M.E., Mai, J.G., Crews, T.E., DeHaan, L.R., Buckley, D.H., 2010. Harvested perennial grasslands provide ecological benchmarks for agricultural sustainability. Agric. Ecosyst. Environ. 137, 3–12.
Gosme, M., De Villemandy, M., Bazot, M., Jeuffroy, M.-H., 2012. Local and neighbourhood effects of organic and conventional wheat management on aphids, weeds, and foliar diseases. Agric. Ecosyst. Environ. 161, 121–129.
Grace, J.B., 2006. Structural Equation Modeling and Natural Systems. Cambridge University Press.
Grace, J.B., Anderson, T.M., Olff, H., Scheiner, S.M., 2010. On the specification of structural equation models for ecological systems. Ecol. Monogr. 80, 67–87.
Grandy, A.S., Loecke, T.D., Parr, S., Robertson, G.P., 2006. Long-term trends in nitrous oxide emissions, soil nitrogen, and crop yields of till and no-till cropping systems. J. Environ. Qual. 35, 1487–1495.
Grandy, A.S., Robertson, G.P., 2007. Land-use intensity effects on soil organic carbon accumulation rates and mechanisms. Ecosystem 10, 59–74.
Halaj, J., Wise, D.H., 2001. Terrestrial trophic cascades: how much do they trickle? Am. Nat. 157, 262–281.
Jabbour, R., 2009. Management effects on epigeal arthropods and soil-dwelling communities during the transition to organic agriculture. Ph.D. Diss. The Pennsylvania State University.
Jonsson, M., Wratten, S.D., Landis, D.A., Gurr, G.M., 2008. Recent advances in conservation biological control of arthropods by arthropods. Biol. Control 45, 172–175.
Karlen, D.L., Berry, E.C., Colvin, T.S., Kanwar, R.S., 1991. Twelve-year tillage and crop rotation effects on yields and soil chemical properties in northeast Iowa. Commun. Soil Sci. Plan 22, 1985–2003.
Kline, R.B., 1998. Principles and Practice of Structural Equation Modeling (1st Edition). The Guilford Press, New York.
Kuo, S., Sainju, U.M., Jellum, E.J., 1997. Winter cover crop effects on soil organic carbon and carbohydrate in soil. Soil Sci. Soc. Am. J. 61, 145–152.
Lamb, E., Shirtliffe, S., May, W., 2011. Structural equation modeling in the plant sciences: an example using yield components in oat. Can. J. Plant Sci. 91, 603–619.
Landis, D.A., Wratten, S.D., Gurr, G.M., 2000. Habitat management to conserve natural enemies of arthropod pests in agriculture. Annu. Rev. Entomol. 45, 175–201.
Letourneau, D.K., Bothwell, S.G., 2008. Comparison of organic and conventional farms: challenging ecologists to make biodiversity functional. Front. Ecol. Environ. 6, 430–438.
Letourneau, D.K., Jedlicka, J., Bothwell, S.G., Moreno, C.R., 2009. Effects of natural enemy biodiversity on the suppression of arthropod herbivores in terrestrial ecosystems. Annu. Rev. Ecol. Evol. Syst. 40, 573–592.
Lewis, D.B., Kaye, J.P., Jabbour, R., Barbercheck, M.E., 2011. Labile carbon and other soil quality indicators in two tillage systems during transition to organic agriculture. Renew. Agric. Food Syst. 26, 342–353.
Liebman, M., Davis, A.S., 2000. Integration of soil, crop and weed management in low-external-input farming systems. Weed Res. 40, 27–47.
Lundgren, J.G., Fergen, J.K., 2011. Enhancing predation of a subterranean insect pest: a conservation benefit of winter vegetation in agroecosystems. Appl. Soil Ecol. 51, 9–16.
Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., Niggli, U., 2002. Soil fertility and biodiversity in organic farming. Science 296, 1694–1697.
Maul, J., Drinkwater, L., 2010. Short-term plant species impact on microbial community structure in soils with long-term agricultural history. Plant Soil 330, 369–382.
Mirsky, S.B., Ryan, M.R., Curran, W.S., Teasdale, J.R., Maul, J., Spargo, J.T., Moyer, J., Grantham, A.M., Weber, D., Way, T.R., Camargo, G.G., 2012. Conservation tillage issues: cover crop-based organic rotational no-till grain production in the mid-Atlantic region, USA. Renew. Agric. Food Syst. 27, 31–40.
Morrill, W.L., 1975. Plastic pitfall trap. Environ. Entomol. 4, 596.
Pimentel, D., Hepperly, P., Hanson, J., Douds, D., Seidel, R., 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. Bioscience 55, 573–582.
Robertson, G.P., Swinton, S.M., 2005. Reconciling agricultural productivity and environmental integrity: a grand challenge for agriculture. Front. Ecol. Environ. 3, 38–46.
Smith, R.G., Barbercheck, M.E., Mortensen, D.A., Hyde, J., Hulting, A.G., 2011. Yield and net returns during the transition to organic feed grain production. Agron. J. 103, 51–59.
Smith, R.G., Jabbour, R., Hulting, A.G., Barbercheck, M.E., Mortensen, D.A., 2009. Effects of initial seed-bank density on weed seedling emergence during the transition to an organic feed-grain crop rotation. Weed Sci. 57, 533–540.
Sutton-Grier, A.E., Kenney, M.a., Richardson, C.J., 2010. Examining the relationship between ecosystem structure and function using structural equation modelling: a case study examining denitrification potential in restored wetland soils. Ecol. Model. 221, 761–768.

Teasdale, J., Rice, C., Cai, G., Mangum, R., 2012. Expression of allelopathy in the soil environment: soil concentration and activity of benzoxazinoid compounds released by rye cover crop residue. Plant Ecol. 213, 1893–1905.
Teasdale, J.R., Coffman, C.B., Mangum, R.W., 2007. Potential long-term benefits of no-tillage and organic cropping systems for grain production and soil improvement. Agron. J. 99, 1297–1305.
Weil, R.W., Islam, K.R., Stine, M., Gruver, J.B., Samson-Liebig, S.E., 2003. Estimating active carbon for soil quality assessment: a simplified method for laboratory and field use. Am. J. Altern. Agric. 18, 3–17.
Zehnder, G., Gurr, G.M., Kühne, S., Wade, M.R., Wratten, S.D., Wyss, E., 2007. Arthropod pest management in organic crops. Annu. Rev. Entomol. 52, 57–80.