Balancing multiple objectives in organic feed and forage cropping systems

Meagan E. Schipanski^{a,*}, Mary E. Barbercheck^b, Ebony G. Murrell^b, Jayson Harper^c, Denise M. Finney^{d,e}, Jason P. Kaye^d, David A. Mortensen^f, Richard G. Smith^h

^a Department of Soil and Crop Sciences, Colorado State University, Fort Collins, CO, USA

^b Dept of Entomology, The Pennsylvania State University, University Park, PA, USA

^c Dept of Agricultural Economics, Sociology, and Education, The Pennsylvania State University, University Park, PA, USA

^d Dept of Ecosystem Science and Management, The Pennsylvania State University, University Park, PA, USA

^e Dept of Biology, Ursinus College, Collegeville, PA, USA

^f Dept of Plant Science, The Pennsylvania State University, University Park, PA, USA

^h Dept of Natural Resources and the Environment, University of New Hampshire, Durham, NH, USA

*Corresponding author:

Meagan Schipanski

Department of Soil and Crop Sciences

Colorado State University

1170 Campus Delivery

Fort Collins, CO 80523-1170

Email: meagan.schipanski@colostate.edu

Phone: 001-970-491-1320

Abstract

Balancing weed suppression, beneficial insect conservation, soil quality and profitability is challenging in organic cropping systems due to reliance on soil disturbance for weed control. We hypothesized that the benefits of tillage can be retained while mitigating adverse impacts on soil quality by alternating tillage with practices that can build soil organic matter. We conducted a four-year experiment in central Pennsylvania, USA, to compare four organic feed and forage cropping systems, each differing in tillage, manure management, and cropping strategies. Each system was designed to address baseline soil quality and weed pressure conditions arising from practices implemented during the previous three-year transition period. To assess cumulative system effects, we established a soybean (*Glycine max*) uniformity trial across all systems in year four. Systems that were in perennial forage for 2 years outperformed annual crop-based systems in weed control and beneficial insect conservation, while maintaining overall profitability over the four-year study period. Soybean yields during the uniformity trial were more than 30% greater in systems that had included perennial forages than in systems with only annual crops. Labile soil carbon pools, an indicator of soil quality, were maintained over time in all systems. Our results indicate that soil quality, weed management, beneficial insect conservation, and profitability can be maintained in organic systems when periodic tillage is coupled with perennial forage crops in rotation.

Keywords: cropping systems; multifunctionality; soil quality; perennial crops; weed management; tillage; arthropod natural enemies

1. Introduction

Organic management systems have the potential to improve multiple ecosystem services over conventional management systems due to reduced reliance on external inputs and increased reliance on biological processes (Cavigelli *et al.*, 2013). However, balancing pest management, soil quality and profitability can be challenging because tillage is often used for weed and pest management, incorporation of animal and green manures, and preparation of seedbeds. Soil disturbance via tillage can also negatively impact key processes that are the foundation of effective organic management. For example, organic production relies on soil-based processes to support pest and disease management (Bond and Grundy, 2001; van Bruggen and Termorshuizen, 2003), nutrient cycling (Drinkwater and Snapp, 2007), and reduce environmental impacts (Tuomisto *et al.*, 2012). Research is necessary to balance the trade-offs between the benefits and disservices of soil tillage to optimize production, profitability and the ecological processes that support organic production.

Over the past decade, there has been growing interest in reduced-till organic management systems (Mirsky *et al.*, 2012; Légère *et al.*, 2013). The development of cover crop termination techniques using a roller-crimper has improved the viability of no-till planting organic crops; however, many organic systems still include inversion tillage within a multi-year rotation (Mirsky *et al.*, 2012). We lack an understanding of the frequency of tillage required to maintain weed control, particularly of perennial weeds, in organic systems. In addition, we lack an understanding of how tillage frequency impacts soil organic matter and beneficial arthropods under different crop rotations and levels of manure input.

69

70 Understanding the role that tillage frequency and intensity play in soil quality is an area of
71 interest that extends beyond organic management systems. For example, the increase in
72 herbicide-resistant weeds is leading some no-till producers to return to periodic tillage as a
73 management tool (Price *et al.*, 2011). Periodic tillage may have short-term negative impacts on
74 labile carbon and microbial pools that do not persist beyond a few years (Franzluebbers *et al.*,
75 1999), but longer-term modeling studies suggest that the effects of periodic tillage can
76 accumulate to negatively affect total soil carbon over time with reduced impacts found for
77 shallow cultivation and non-inversion tillage (Conant *et al.*, 2007). Similarly, a recent meta-
78 analysis indicates that reducing the intensity of tillage in organic systems can improve soil C
79 stocks (Cooper *et al.*, 2016).

80

81 In addition to tillage frequency, crop rotations can also exert a strong influence on weed density,
82 beneficial arthropods, and soil quality. For example, Cardina *et al.* (2009) found that more
83 diverse, corn-oat-hay rotations had lower weed density compared with continuous corn under no-
84 till management. While less-disturbed cropping systems often have greater insect predator
85 populations, beneficial insect species also respond to previous cash or winter cover crops
86 (Holland and Luff, 2000; Thorbeck and Bilde, 2004; Lundgren and Fergen 2010). Integrating
87 perennial crops, which typically have larger root systems than annuals, into rotations can also
88 contribute to soil quality improvements in addition to reducing tillage frequency (Zan *et al.*,
89 2001).

90

Organic cropping systems managed with tillage can also maintain or build local soil organic matter, a central component of soil quality, through additions of carbon-rich manure or composts as well as increased use of cover crops (Teasdale *et al.*, 2007). Increasing carbon inputs can offset the stimulatory effect of tillage on soil organic matter decomposition. Therefore, balancing soil quality, beneficial arthropod conservation, and weed control may be achieved through a reduction of tillage frequency and intensity coupled with diversified crop rotations and the use of organic soil amendments.

Cropping systems experiments are an important tool for understanding how management strategies influence overall system performance over time. For example, long-term cropping systems studies have highlighted the relative effects of conventional, organic, no-till, reduced input, and conservation tillage systems on a broad suite of agroecosystem functions (Mäder *et al.*, 2002; Syswerda and Robertson, 2014). Within organic management systems, cropping systems studies have allowed us to understand the relative effect of input strategies and crop rotations on yield and profitability (Teasdale *et al.*, 2007; Caldwell *et al.*, 2014) and to identify key drivers of critical ecosystem processes (Finney *et al.*, 2015).

One of the challenges with systems experiments is how to allow them to evolve over time using adaptive management strategies. Implementing changes in long-term systems experiments can make it difficult to interpret whether changes are an effect of the newly imposed management system or the previous management legacy. We implemented a novel approach of layering a new experiment across a previous cropping systems experiment that intentionally utilized the soil quality and weed community legacies of the previous experiment. The previous study focused on

identifying successful cover crop and tillage strategies during the 3-year transition phase from conventional to organic management of feed and forage crops in central Pennsylvania. We found that reduced tillage intensity had a positive effect on soil quality indicators, but a negative effect on weed management and crop yields (Jabbour and Barbercheck, 2009; Lewis *et al.*, 2011; Smith *et al.*, 2011; Schipanski *et al.*, 2014). In particular, the switch from moldboard plow to chisel plow contributed to an increased density of a problematic perennial weed (*Cirsium arvense*, Canada thistle). The second 4-year study period, which we analyze in this paper, was designed to assess the potential of different cropping systems to reduce or maintain initial *C. arvense* densities while also maintaining or improving soil quality and beneficial arthropod populations. We compared four organic feed and forage cropping systems that differed in tillage frequency and patterns of annual and perennial crops in rotation. We predicted that adverse effects of tillage on soil quality could be mitigated by alternating soil disturbance for weed control with activities that increase soil carbon and beneficial arthropod habitat while maintaining profitability. To evaluate the integrated effect of the different cropping systems, we conducted a one-year uniformity trial at the end of the experiment.

2. Methods

2.1 Experimental site and design

The field experiment was 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 PA is continental with 975 mm mean annual precipitation and mean monthly temperatures ranging from 3°C (January) to 21.6°C (July). The dominant soil type at this location is Hagerstown silt

loam (Fine, mixed, semiactive, mesic, Typic Hapludalf). Soil texture was predominantly clay loam with spatial variability in silt (range of 45.5-54.7%) and sand (14.0-26.4%).

The field experiment was established twice, in the fall of 2007 for the first start (Start 1) and again in fall 2008 for the second start (Start 2). Four rotation systems were established in a randomized complete block design with four replications. Each plot was 0.067 ha. The rationale supporting the approach to management in each system was based on the population densities of Canada thistle (*Cirsium arvense*, a perennial weed) that were present at the end of the previous experiment evaluating the effects of tillage intensity on weed dynamics and soil quality (Schipanski *et al.*, 2014). Systems 1 and 3 were designed to focus on reducing *C. arvense* populations and systems 2 and 4 were designed to maintain low *C. arvense* populations (Table 1). Specifically, system 1 was designed to reduce perennial weed pressure through high initial disturbance frequency with short-season cover crops in year one followed by two years of perennial forage to build soil quality. System 2 was designed to suppress perennial weeds through high biomass production of annual forage in year one with reduced disturbance followed by two years of perennial forage to build soil quality. System 3 was designed to reduce perennial weeds through intensive soil disturbance during a tilled summer fallow in year one followed by annual crops planted with and without tillage in years two and three, respectively. System 4 was designed to suppress perennial weeds and build soil quality through low frequency soil disturbance and the maintenance of constant biomass cover in years one and two, followed by tillage and annual cropping year three.

The four experimental systems varied in terms of crop rotations, tillage frequency, and manure applications (Table 1). All systems were moldboard plowed and planted with a cereal rye (*Secale cereale*) and hairy vetch (*Vicia villosa*) cover crop in August of experimental year 0 (2007 for Start 1 and 2008 for Start 2). We define ‘conventional tillage’ as inversion tillage with a moldboard plow. System 1 employed a sequence of conventionally tilled summer cover crops in year one to reduce populations of *C. arvense* followed by two years of a perennial cash crop, alfalfa (*Medicago sativa*). System 2 employed a single cash crop established with conventional tillage in the summer of year one (sudangrass, *Sorghum bicolor* ssp. *drummondii*) followed by a fall fallow period to reduce annual weeds. An alfalfa and orchardgrass (*Dactylis glomerata*) biculture was established in year two and maintained for two years. In System 3, the initial cereal rye/hairy vetch cover crop was allowed to grow through July of year one and was followed by a tilled fallow to reduce *C. arvense* populations. The tilled fallow included shallow, non-inversion tillage with an S-tine cultivator 3 times over a 2-month period. A small grain cash crop (cereal rye) was established in fall year one and harvested in July year two, followed by a summer planted triticale (*Triticale hexaploide*) and hairy vetch cover crop; both crops were managed with conventional tillage. In year three, corn (*Zea mays*) was planted without tillage. System 4 sought to re-build soil organic matter through successive cover crops established without tillage prior to planting conventionally tilled corn in year 3. Thus, each system employed distinct approaches to managing weeds in ways that might deplete organic matter (e.g. tillage and fallow periods) alternated with practices that should rebuild organic matter (cover crops, perennial crops, no-till cash crops, manure inputs). While this diverse and realistic array of practices is a strength of the project, it also represented a challenge, since all treatments differed in multiple ways. Thus, to assess cumulative system effects and because yield comparisons were difficult to make across

the diversity of crops in each rotation year, we established a uniformity trial across all systems in year four. All plots were plowed and disked and planted to soybeans in June of year four. Soybean (*Glycine max*) was selected because of its biological nitrogen fixation potential to equalize differences in background nitrogen levels. Within each main plot during the uniformity trial, we established subplots (3m x 3m) of a non-nodulating soybean variety (seed provided by J. Orf, University of Minnesota) to assess system effects on soil nitrogen availability.

All systems used tillage, but tillage frequency varied across treatments. The shading in Table 1 distinguishes between crops established without tillage or with conventional tillage. Conventional tillage is defined as inversion tillage with a moldboard plow (Table 1). In conventionally tilled cash crops (corn and soybeans), we used tillage and inter-row cultivation to manage in-season weeds. During periods managed without tillage (Table 1), no plowing operations were performed prior to crop establishment and cover crops were terminated by mowing or rolling. We applied manure in the spring prior to sorghum sudangrass (System 2, year one) and corn (Systems 3 and 4, year three) production. We determined manure application rates following standard nutrient management practices used by farmers in the region as outlined in the Penn State Agronomy Guide (Table 1, Beegle, 2008). For a detailed summary of manure N inputs, see Finney *et al.* (2015).

2.2 Data collection

2.2.1 Weeds

Weed density and biomass were sampled annually within each plot in September to capture data at peak biomass and prior to senescence. Within each plot all weeds were counted, identified,

and clipped within five replicate 0.25 m² quadrats. For rhizomatous weeds, such as *C. arvense*, each stem was counted as one individual. Biomass samples were dried at 55°C and weighed.

2.2.2 Yields

Yields are difficult to compare across management systems during the first three years of the experiment due to the different rotations (Table 2). Therefore, we focused yield analysis on the uniformity trial conducted at the end of the experiment in year four. Soybean seed yields during the uniformity trial were sampled from the center five rows of each plot (0.021 ha) using a combine with a weighing system. A subsample was collected to correct yields for moisture content.

Aboveground biomass of the nodulating and non-nodulating soybeans was measured by clipping all aboveground tissues from 1.5-m² within the center of 3m x 3m subplots prior to leaf senescence in September of each year. Biomass samples were dried, ground, and analyzed for total C and N using an elemental analyzer (EA1110 Elemental Analyzer, CE Instruments).

2.2.3 Soil quality indicators

Soils were sampled each fall (September/October). At each sampling, three composite soil samples were collected from random locations within each plot. Each sample comprised 15 individual soil cores (2.5-cm diameter x 15-cm depth).

Permanganate oxidizable C (POXC) was measured as an indicator of soil labile C following protocols developed by 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 $\text{pH} > 7.2$ using sodium hydroxide (NaOH). Samples were shaken for 2 minutes and then allowed to settle for 10 minutes. 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 spectrophotometer at 550 nm. We assumed 9 mol of organic C were oxidized for every 1 mole of permanganate reduced.

Soil bulk density was measured in fall of year 0 and spring and fall of year four by collecting soil cores at three depths (i.e., 0-10 cm, 10-20 cm, and 20-30 cm) in two random locations per plot. A hammer-driven core sampler was used to obtain intact soil cores at each depth using aluminum rings (7.62-cm length x 7.62-cm inner diameter). Soil samples were dried and weighed and sieved to 2mm for coarse rock fragment correction (Blake and Hartge, 1986). Soil carbon data were adjusted from concentration (mg/kg soil) to content (g/m^2) using a weighted average of the 0-10cm and 10-20cm bulk density measurements.

2.2.4 Predatory arthropods

We focused on ground-dwelling predatory arthropods as an indicator of rotation impacts on beneficial insects and as an indicator of biological pest management potential (Cardinale *et al.*, 2003; Symondson *et al.*, 2002). Pitfall traps were used to assess activity-density of five major arthropod groups: Spiders (Order Araneae), harvestmen (Order Opiliones), ground and tiger beetles (Order Coleoptera, Family Carabidae), rove beetles (Order Coleoptera, Family Staphylinidae), and centipedes (Order Chilopoda). Of the 17 orders or families that were

collected from our pitfall traps, these five taxa represented 31% by abundance and 42% by taxon richness of all arthropods captured in the traps. Additionally, these taxa consist primarily of generalist predators (Lang 2003) whose activity-densities can be assessed using pitfall traps (Woodcock, 2005; Prasifka *et al.*, 2007). Three traps were placed in each plot on the following dates: 11/2/2006 (Start 1 only), 11/1/2007 (Start 2 only), 8/11/2008 (Start 1 only), 9/3/2009, 8/9/2010, 9/19/2011, and 8/27/2012 (Start 2 only). Each trap consisted of a plastic deli container 11.4 cm in diameter and 12.9 cm deep, containing a small sample cup in the bottom (8.7 cm diameter x 6 cm depth) with a plastic funnel placed on top to prevent accidental trapping of larger organisms. Each trap was buried with the container lip flush with the soil surface, and its sample cup was filled with 40 mL ethylene glycol. Traps were collected after 72 h. Trapped arthropods were preserved in scintillation vials with 80% ethanol plus 1 mL glycerol for storage, and later identified to order or family in the laboratory. Pitfall traps were removed from the field after each sampling event.

2.2.5 Economic analysis

Enterprise budgets were constructed based on actual field activities and costs of inputs for the four systems and two starts over the four years of the study, plus the initial cover crop establishment phase. Machinery costs were based on the type of implements used in the experiments adjusted to machinery sizes and tractors that are typically used on Pennsylvania dairy farms. The budgets were constructed to estimate both variable costs (those that vary with the level and intensity of production like labor, fuel, soil amendments, seed, repairs, and harvest) and fixed costs (those that relate to the ownership of machinery like depreciation, interest, and insurance). No charges for management or land were included in the budgets.

Because the overall profitability of these systems depended heavily on the sequencing of operations in previous years, it was necessary to evaluate the cash flow streams generated by each system over time. Annual cash flow estimates for the systems were calculated based on three price scenarios (low, medium, and high) and actual yields obtained in the experiments. The net present value of the cash flow for each production system was then calculated for the three price scenarios. Net present value analysis compares the value of a dollar today to the value of a dollar in the future, taking inflation and decision maker time preferences into account by use of a discount rate. The net present value expresses a projected stream of future cash flows as a single value and allows for the direct comparison of alternatives. A production system with a cash flow stream that generates a positive net present value would merit consideration for adoption. A 6% discount rate was used in the evaluation. This is an acceptable rate to use given current inflationary expectations and the anticipation of generating a moderate level of return on capital.

2.3 Data analysis

We conducted all soil and weed analyses using mixed models in JMP v.11 (SAS, Cary, NC). Start and block were included as nested random factors in mixed models comparing management systems. Weed data were log transformed to meet normal distribution model assumptions. For analysis of temporal trends, rotation year was included as a fixed factor. Total activity-densities of the five arthropod taxa combined were analyzed by system for each year using mixed models in SAS (PROC GLIMMIX, SAS 9.4) with a log-normal distribution. Significant differences among systems were assessed using pairwise comparisons with a Tukey adjustment.

3. Results

Results from the soybean uniformity trial at the end of the 4-year systems experiment indicate that the perennial-based Systems 1 and 2 outperformed the annual-based Systems 3 and 4 in annual weed control, while all systems maintained perennial weed control. Density of the target perennial weed, *C. arvense*, decreased or was maintained at low levels across all systems. *Cirsium arvense* density in year three was significantly reduced from year 0 in Systems 1 and 3, which had higher initial *C. arvense* density due to reduced tillage intensity during the previous experiment (Figure 1). The system with the lowest tillage frequency during this experiment, System 4, had higher *C. arvense* density in year three; however, density was not significantly different from year 0 or from the other three systems in year three (Figure 1). Perennial weed biomass was low across all systems in year four when the soybean uniformity trial was managed with inversion tillage prior to planting and subsequent cultivation events (Figure 2). *C. arvense* density was less than 0.5 plants m⁻² across all systems during the uniformity trial.

Annual weeds, in contrast, differed across systems during the uniformity trial. Annual weed biomass was four times greater in Systems 3 and 4 following corn than in Systems 1 and 2 following alfalfa and alfalfa/orchardgrass, respectively. Dominant annual weed species included *Amaranthus spp.* and *Chenopodium album* that represented 41% and 37%, respectively, of the total annual weed biomass across all systems in year four (community data not shown).

Weed biomass was inversely correlated with yields in the soybean uniformity trial ($r = -0.81$, $P < 0.0001$). Average soybean yields in the uniformity trial were more than 30% greater in Systems 1 and 2, than in Systems 3 and 4 (Figure 3).

319

320 Soil quality indicators generally did not differ across management systems with the exception of

321 labile soil C. Permanganate oxidizable C (POXC) was higher in System 3 than System 1 during

322 the uniformity trial in year four (Figure 4). Bulk density, another soil quality indicator, did not

323 differ across management systems at the start or end of the experiment (Supplementary Table 1).

324

325 Nitrogen uptake by non-nodulating soybean was greater following alfalfa-orchardgrass in

326 System 2 than following corn receiving manure in Systems 3 and 4 (Figure 5). For both systems

327 following alfalfa in mixture or monoculture non-nodulating soybeans took up 150 kg N/ha in

328 aboveground biomass, while in Systems 3 and 4 uptake was less than 100 kg N/ha.

329

330 Predatory arthropod abundances did not differ among systems during the transition year or the

331 first year of the study (Figure 6). Beginning at the fall sampling in year two, predators had

332 significantly higher activity-densities in both perennially-based systems (Systems 1 and 2) than

333 in the annual-based systems (Systems 3 and 4, Figure 6). System 1 retained higher arthropod

334 abundances in year three than Systems 3 and 4, when both annual systems were planted to corn.

335 During the soybean uniformity year, predator activity-densities were reduced across all systems,

336 but remained significantly higher in the perennial-based systems than in System 4 (Figure 6).

337

338 System 2, a system with annual and perennial forages, was more profitable than the other

339 systems. Averaged across Start 1 and 2, System 2 performed well regardless of the price

340 scenario. All systems had a positive net present value (NPV) when averaged across price

341 scenarios, a single measure of the overall value of the individual year cash flows over the full 4-

year rotation (Figure 7). System 2 had positive cash flows for three years and a higher NPV. The NPV of systems 1, 3 and 4, were similar though annual cash flows varied across the systems (Figure 7). When separated by Start, the lower yields in Start 2 (Table 2) contributed to negative NPV for all systems except at the high price scenario. System 2 had a greater NPV than the other systems across both starts.

4. Discussion

Our results provide insights into the frequency of soil disturbance required to reduce perennial weeds, such as *C. arvense*, in organic cropping systems while balancing other management objectives. The integration of perennial legume-based forages into annual feed and forage rotations provided the broadest suite of functions, including reducing weed pressure, increasing soil nitrogen supply, supporting beneficial soil arthropods, and maintaining soil quality and net profitability. Soil quality was also maintained in annual-based crop rotations that received periodic manure additions.

Perennial weed density was influenced by the frequency of soil disturbance over the 4 year rotation. System 3, which included tillage in 3 of the 4 years, reduced *C. arvense* density from initial density levels (Figure 1). In contrast, System 4, which had the least frequent soil disturbance with tillage only in 1 of 4 years, showed a shift toward increasing *C. arvense* density by year three, but the difference was not significant. While this study focused primarily on the frequency of tillage, our previous study found similar results when looking at reducing tillage intensity (Smith *et al.*, 2011; Schipanski *et al.*, 2014). Long-term no-till and reduced tillage systems often result in increasing perennial weed populations (Blackshaw *et al.*, 1994; Peigné *et*

al., 2007), but little research has been conducted to understand how periodic tillage may influence perennial weeds. Our results suggest that inversion tillage in one out of every three years may be sufficient to maintain perennial weed control in organic systems in conjunction with other standard practices such as good crop management that maintains plant competition.

Perennial crop competition paired with periodic mowing may provide an alternative method to soil disturbance for control of annual and perennial weeds. The perennial forages were more effective than annual crops at suppressing annual weeds. Even with inversion tillage and cultivation events, annual weed pressure was higher following corn than following perennial forages (Figure 2). Perennial forages reduce both annual and perennial weed pressure in the following crop and can shift the composition of weed communities over time (Entz *et al.*, 2002). In particular, increasing phenological diversity in rotations through the inclusion of both annual and perennial crops can reduce annual weed pressure in organic cropping systems (Teasdale *et al.*, 2004). Perennial forages may also reduce the weed seedbank due to increased weed seed predation (Meiss *et al.*, 2010).

Perennial legume forages also supported increased N uptake by the following annual crop. The N uptake by the non-nodulating soybeans was similar to estimates of the N contributions of perennial alfalfa and alfalfa-mixtures that are commonly around 150-200 kg N/ha from biological N fixation (Russelle and Birr, 2004). Approximately 50-60% of this N becomes available in the first year, while the remainder is released more slowly over multiple years (Yost *et al.*, 2013). This N input represents an important economic benefit for organic producers who do not have an inexpensive source of manure. However, the large pulse of N following perennial

legume termination can also result in potential N leaching and N₂O emissions (Jensen *et al.*, 2011; Finney *et al.*, 2015). The alfalfa-orchardgrass mixture provided a similar amount of N as the pure alfalfa stand. Mixtures tend to have improved N synchrony with crop demand due to the higher C:N of the residue (Wagger *et al.*, 1998).

Despite the short-term benefits of perennial forage increasing readily mineralizable N, the systems with perennial forages did not result in higher labile soil organic matter pools. In particular, System 2 that was designed to build soil quality through high biomass annual and perennial forages, had labile soil C levels that were less than or equivalent to more frequently tilled annual systems such as System 3 (Figure 4). Perennial plants tend to increase soil carbon stocks at a faster rate than annuals, but the rate of soil carbon accumulation varies considerably with region, species, and management context (Guo and Gifford, 2002; Machmuller *et al.*, 2015). The time scale of our study may have limited our ability to detect the impact of perennial root systems on soil C pools.

Labile soil C and N pools were influenced by an interactive effect of manure additions and tillage frequency. Tillage is known to reduce soil C pools, while manure additions can increase soil organic C pools under both tilled and no-till systems (Mikha and Rice, 2004). The higher POXC pools in System 3 relative to System 1 at the end of the experiment were likely due to higher starting levels as a result of reduced tillage during the previous experiment and the external organic matter inputs via manure applications. Annual POXC levels increased following each manure addition (Figure 4; see System 2, year 1; Systems 3 and 4, year 3). The increase in SOM in many long-term organic systems trials are often supported both by increased plant C

inputs and by applications of manures or composts that effectively offset C losses due to tillage events (e.g., Teasdale *et al.*, 2007). The source of these C inputs can influence the net C balance of a farming operation. While the source may be from within the same farm in integrated crop-livestock systems, manures and composts applied to organic farms are often an imported nutrient source subsidized by nearby conventional operations.

The activity-densities of predatory arthropods in the perennially-based systems in years two and three is not surprising, given that alfalfa fields are known for supporting highly diverse predator communities (Greze *et al.*, 2014). Less-disturbed systems typically have greater predator populations (House and Stinner, 1983), but individual species can respond idiosyncratically to tillage and previous cash or winter cover crops (Holland and Luff, 2000, Lundgren and Fergen, 2010). Both tillage and previous cropping history can influence arthropod communities. The higher activity-densities in our perennial systems, relative to the annual systems, were retained even during the soybean uniformity trial. In a previous study, predator abundance was greater in corn following an autumn-planted, spring-killed grass cover crop, *Elymus trachycaulus*, compared to corn without a preceding cover crop (Lundgren and Fergen, 2010). Activity-densities of the carabid beetle, *Harpalus rufipes* DeGeer, were greater in conventionally-tilled corn following a pea/oat–cereal rye/hairy vetch cover crop system compared to treatments without a preceding cover crop (Shearin *et al.*, 2008). The activity-densities of *H. rufipes* were greatest in systems representing a medium level of disturbance among the various systems (Shearin *et al.*, 2008), thus suggesting that for at least some predators, some level of disturbance may be beneficial for species diversity.

Our results suggest that rotations with a mixture of annual and perennial crops have the best potential for maintaining positive cash flows over time across variable weather years. System 2 had the highest average NPV over the full four-year experiment due to a combination of factors. The alfalfa/orchardgrass yields maintained positive cash flows in years two and three and then the weed suppressive effect of the perennial forage, greater N supply, and greater predatory arthropod density likely all contributed to higher soybean yields in year four. The challenge for some producers in certain parts of the U.S. in integrating more perennial crops into rotations is the need for a relatively local market or the integration of on-farm crop-livestock systems.

5. Conclusions

Our goal was to identify key principles for managing organic cropping systems for multiple agronomic and agri-environmental objectives. Our results indicate that multiple management tools are required to manage for multiple outcomes. Reducing tillage frequency to once every two to three years, coupled with maintaining crop competition, successfully maintained perennial weed control without reducing soil quality. The integration of perennial forages has the potential to provide better annual weed control, conservation of arthropod natural enemies, and profitability than annually tilled systems. External manure applications can offset tillage impacts on labile soil C and maintain or improve soil quality. In organic feed and forage systems, overall system profitability is largely dependent on reducing input costs, maintaining annual cash flows, and effective weed and beneficial insect management. While organic agriculture is often criticized for negative environmental impacts of tillage on soils, here we show that reducing tillage by rotating tillage practices and soil building events over time is a viable strategy to

maintain low weed populations without diminishing soil labile C, profitability, and beneficial soil arthropods.

Acknowledgements

We would like to thank S. Eckert, D. Sandy, S. Smiles, S. Harkcom, and C. Mullen for their assistance with field management and data collection. We would like to thank our project advisory board for their helpful input, including J. Moyer, L. Zuck, B. Snyder, R. Robertson, T. DuPont, L. Garling, P. Yoder, A. Ziegler, K. Yoder, and W. Esbenshade. The manuscript was improved by helpful input from anonymous reviewers. This project was funded by USDA CSREES-ICGP Risk Avoidance and Mitigation Program (grant no. 2007-03085 to M.E. Barbercheck).

References

- Beegle D. 2008. Section 2: Soil fertility management. Pennsylvania State Agronomy Guide 2007–2008. The Pennsylvania State University, University Park, PA.
- Blackshaw, R.E., Larney, F.O., Lindwall, C.W., Kozub, G.C., 1994. Crop rotation and tillage effects on weed populations on the semi-arid Canadian prairies. *Weed Technology*, 231-237.
- Blake, G.R., and K.H. Hartge. 1986. Bulk density. p. 363–375. In A. Klute (ed.) *Methods of soil analysis*. Part 1. 2nd ed. Agronomy Monographs 9. ASA and SSSA, Madison, WI.
- Bond, W., Grundy, A.C. 2001. Non-chemical weed management in organic farming systems. *Weed Research* 41, 383-405.
- Caldwell, B., Mohler, C.L., Ketterings, Q.M., DiTommaso, A. 2014. Yields and profitability during and after transition in organic grain cropping systems. *Agronomy Journal* 106, 871-880.
- Cardina, J., Herms, C.P., Doohan, D.J. 2009. Crop rotation and tillage system effects on weed seedbanks. *Weed Science* 50, 448-460.
- Cardinale, B. J., Harvey, C. T., Gross, K., Ives, A. R. 2003. Biodiversity and biocontrol: emergent impacts of a multi- enemy assemblage on pest suppression and crop yield in an agroecosystem. *Ecology Letters* 6, 857-865.

- Cavigelli, M.A., Mirsky, S.B., Teasdale, J.R., Spargo, J.T., Doran, J. 2013. Organic grain cropping systems to enhance ecosystem services. *Renewable Agriculture and Food Systems* 28, 145-159.
- Conant, R.T., Easter, M., Paustian, K., Swan, A., Williams, S. 2007. Impacts of periodic tillage on soil C stocks: A synthesis. *Soil and Tillage Research* 95, 1-10.
- Cooper, J., Baranski, M., Stewart, G., et al. 2016. Shallow non-inversion tillage inorganic farming maintains crop yields and increases soil C stocks: a meta-analysis. *Agronomy for Sustainable Development* 36, 22. doi:10.1007/s13593-016-0354-1
- Drinkwater, L.E. and Snapp, S.S. 2007. Nutrients in agroecosystems: rethinking the management paradigm. *Advances in Agronomy* 92, 163-186.
- Entz, M.H., Baron, V.S., Carr, P.M., Meyer, D.W., Smith, S. and McCaughey, W.P. 2002. Potential of forages to diversify cropping systems in the Northern Great Plains. *Agronomy Journal* 94, 240-250.
- Finney, D.M., Eckert, S.E. and Kaye, J.P. 2015. Drivers of nitrogen dynamics in ecologically based agriculture revealed by long-term, high-frequency field measurements. *Ecological Applications* 25(8), 2210-2227.
- Franzuebbers, A., Langdale, G., Schomberg, H. 1999. Soil carbon, nitrogen, and aggregation in response to type and frequency of tillage. *Soil Science Society of America Journal* 63, 349-355.
- Greze, A. A., Zaviezo, T., and Gardiner, M. M. 2014. Local predator composition and landscape affects biological control of aphids in alfalfa fields. *Biological Control*, 76:1-9.
- Guo, L.B., Gifford, R. 2002. Soil carbon stocks and land use change: a meta analysis. *Global Change Biology* 8, 345-360.
- Holland, J. M., and M. L. Luff. 2000. The effects of agricultural practices on Carabidae in temperate agroecosystems. *Integrated Pest Management Review* 5, 105-125.
- House, G. J., Stinner, B. R. 1983. Arthropods in no-tillage soybean agroecosystems: community composition and ecosystem interactions. *Environmental Management* 7, 23-28.
- Jabbour, R., Barbercheck, M. 2009. Soil management effects on entomopathogenic fungi during the transition to organic agriculture in a feed grain rotation. *Biological Control* 51, 435-443.
- Jensen, E.S., Peoples, M.B., Boddey, R.M., Gresshoff, P.M., Hauggaard-Nielsen, H., J.R. Alves, B., Morrison, M.J. 2011. Legumes for mitigation of climate change and the provision of feedstock for biofuels and biorefineries. A review. *Agronomy for Sustainable Development* 32, 329-364.
- Lang, A. 2003. Intraguild interference and biocontrol effects of generalist predators in a winter wheat field. *Oecologia*, 134:144-153.
- Légère, A., Shirliffe, S.J., Vanasse, A., Gulden, R.H. 2013. Extreme grain-based cropping systems: When herbicide-free weed management meets conservation tillage in northern climates. *Weed Technology* 27, 204-211.
- 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. *Renewable Agriculture and Food Systems* 26, 342-353.
- Lundgren, J.G. and Fergen, J.K. 2010. The effects of a winter cover crop on *Diabrotica virgifera* (Coleoptera: Chrysomelidae) populations and beneficial arthropod communities in no-till maize. *Environmental entomology* 39(6), 816-828.

- Machmuller, M.B., Kramer, M.G., Cyle, T.K., Hill, N., Hancock, D., Thompson, A. 2015. Emerging land use practices rapidly increase soil organic matter. *Nature Communications* 6. doi:10.1038/ncomms7995.
- Mäder, P., Fliessbach, A., Dubois, D., Gunst, L., Fried, P., Niggli, U. 2002. Soil fertility and biodiversity in organic farming. *Science* 296, 1694-1697.
- Meiss, H., Le Lagadec, L., Munier-Jolain, N., Waldhardt, R., Petit, S. 2010. Weed seed predation increases with vegetation cover in perennial forage crops. *Agriculture, Ecosystems & Environment* 138, 10-16.
- Mikha, M.M., Rice, C.W. 2004. Tillage and manure effects on soil and aggregate-associated carbon and nitrogen. *Soil Science Society of America Journal* 68, 809-816.
- 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. 2012. Conservation tillage issues: Cover crop-based organic rotational no-till grain production in the mid-Atlantic region, USA. *Renewable Agriculture and Food Systems* 27, 31-40.
- Peigné, J., Ball, B.C., Roger-Estrade, J. and David, C. 2007. Is conservation tillage suitable for organic farming? A review. *Soil Use and Management* 23(2), 129-144.
- Prasifka, J. R., Lopez, M. D., Hellmich, R. L., Lewis, L. C., and Dively, G. P. 2007. Comparison of pitfall traps and litter bags for sampling ground- dwelling arthropods. *Journal of Applied Entomology*, 131:115-120.
- Price, A.J., Balkcom, K., Culpepper, S., Kelton, J., Nichols, R., Schomberg, H. 2011. Glyphosate-resistant Palmer amaranth: a threat to conservation tillage. *Journal of Soil and Water Conservation* 66, 265-275.
- Russelle, M.P., Birr, A.S. 2004. Large-scale assessment of symbiotic dinitrogen fixation by crops. *Agronomy Journal* 96, 1754-1760.
- Schipanski, M.E., Smith, R.G., Gareau, T.L.P., Jabbour, R., Lewis, D.B., Barbercheck, M.E., Mortensen, D.A., Kaye, J.P. 2014. Multivariate relationships influencing crop yields during the transition to organic management. *Agriculture, Ecosystems & Environment* 189, 119-126.
- Shearin, A.F., Reberg-Horton, S.C., Gallandt, E.R. 2008. Cover crop effects on the activity-density of the weed seed predator *Harpalus rufipes* (Coleoptera: Carabidae). *Weed Science* 56, 442-450.
- 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. *Agronomy Journal* 103, 51-59.
- Symondson, W. O. C., Sunderland, K. D., Greenstone, M. H. 2002. Can generalist predators be effective biocontrol agents? *Annual Review of Entomology* 47, 561-594.
- Syswerda, S.P., Robertson, G.P. 2014. Ecosystem services along a management gradient in Michigan (USA) cropping systems. *Agriculture, Ecosystems & Environment* 189, 28-35.
- Teasdale, J.R., Mangum, R.W., Radhakrishnan, J., Cavigelli, M.A. 2004. Weed seedbank dynamics in three organic farming crop rotations. *Agronomy Journal* 96, 1429-1435.
- Teasdale, J.R., Coffman, C.B., Mangum, R.W. 2007. Potential benefits of no-tillage and organic cropping systems for grain production and soil improvement. *Agronomy Journal* 99, 1297 – 1305.
- Thorbek, P., Bilde, T. 2004. Reduced numbers of generalist arthropod predators after crop management. *Journal of Applied Ecology* 41, 526-538.

576 Tuomisto, H.L, Hodge, I.D., Riordan, P., Macdonald, D.W. 2012. Does organic farming reduce
 577 environmental impacts? – A meta-analysis of European research. *Journal of*
 578 *Environmental Management* 112, 309-320.
 579 van Bruggen, A. H., Termorskuizen, A. J. 2003. Integrated approaches to root disease
 580 management in organic farming systems. *Australasian Plant Pathology* 32, 141-156.
 581 Waggoner, M., Cabrera, M., Ranells, N. 1998. Nitrogen and carbon cycling in relation to cover
 582 crop residue quality. *Journal of Soil and Water Conservation* 53, 214-218.
 583 Weil, R.R., Islam, K.R., Stine, M.A., Gruver, J.B., Samson-Liebig, S.E. 2003. Estimating active
 584 carbon for soil quality assessment: A simplified method for laboratory and field use.
 585 *American Journal of Alternative Agriculture* 18, 3-17.
 586 Woodcock, B. A. 2005. Pitfall trapping in ecological studies. In *Insect Sampling in Forest*
 587 *Ecosystems* [ed. S. Leather], Ch. 3, pp 37-57. Blackwell Science Ltd.: Malden, MA
 588 USA.
 589 Yost, M.A., Coulter, J.A., Russelle, M.P. 2013. First-year corn after alfalfa showed no response
 590 to fertilizer nitrogen under no-tillage. *Agronomy Journal* 105, 208-214.
 591 Zan, C.S., Fyles, J.W., Girouard, P., and Samson, R.A. 2001. Carbon sequestration in perennial
 592 bioenergy, annual corn and uncultivated systems in southern Quebec. *Agriculture,*
 593 *Ecosystems & Environment* 86, 135–144.

Table 1. The previous and current experiment management strategies for 4 organic feed and forage cropping systems, including the cumulative number of inversion and secondary tillage events and the 4-year cropping sequence for each system initiated in 2007 (Start 1) and 2008 (Start 2) near Rock Springs, PA.

	System 1		System 2		System 3		System 4	
Previous experiment management	Reduced tillage		Full tillage		Reduced tillage		Full tillage	
Management strategy	<i>Perennial crops with high disturbance initially to reduce perennial weed pressure</i>		<i>Perennial and annual forages with reduced disturbance to rebuild soil quality</i>		<i>Annual crops with disturbance, including high intensity tilled fallow, to reduce perennial weed pressure</i>		<i>Annual crops with low disturbance to rebuild soil quality</i>	
Inversion tillage events in Yrs 1-3 ^a	3		2		2		1	
Secondary tillage events in Yrs 1-3 ^b	8		7		8		8	

Year	Start 1	Start 2	Season	Cropping Sequence			
0	2007	2008	Fa	Rye & hairy vetch	Rye & hairy vetch	Rye & hairy vetch	Rye & hairy vetch
1	2008	2009	Wi	Mustard	Sudangrass* (60/50) ^c	Tilled fallow	Buckwheat
			Sp	Buckwheat			
			Su	Oats	Fallow	Rye*	Rye & hairy vetch
			Fa	Fallow			
2	2009	2010	Wi	Alfalfa*	Alfalfa/orchardgrass*	Triticale & hairy vetch	Rye
			Sp				
			Su			Corn* (114/123)	Corn* (299/258)
			Fa				
3	2010	2011	Wi			Fallow	Fallow
			Sp				
			Su			Soybean*	Soybean*
			Fa				
4	2011	2012	Wi			Fallow	Fallow
			Sp				
			Su			Soybean*	Soybean*
			Fa				

Adapted from Finney et al. (2015)

^a Shaded areas represent rotation phases managed without tillage and un-shaded regions represent crop phases managed with inversion tillage for crop establishment or manure incorporation prior to crop establishment.

^b Secondary tillage events include non-inversion soil disturbance events such as field cultivation, tine weeding or discing.

^cManure application rates (Mg/ha) are presented in parentheses for Start 1 and Start 2, respectively.

* Crops marked with an asterisk (*) were harvested as cash crops.

Table 2. Mean crop yields (Mg/ha) for each cropping system and experimental Start. Standard errors of the mean are presented in parentheses.

Start	System	Crop	Rotation Year			
			1	2	3	4
1	1	Alfalfa		3.6 (0.1)	12.4 (0.6)	
		Soybean				2.8 (0.06)
	2	Sudex	10.9 (1.9)			
		Alfalfa/Orchardgrass		3.8 (0.2)	11.0 (0.9)	
		Soybeans				2.7 (0.1)
	3	Rye		10.0 (1.4)		
		Corn			6.5 (0.9)	
		Soybean				2.3 (0.08)
	4	Corn			8.0 (0.6)	
		Soybean				2.5 (0.07)
2	1	Alfalfa		4.5 (0.3)	9.1 (0.3)	
		Soybean				2.8 (0.06)
	2	Sudex	5.6 (0.2)			
		Alfalfa/Orchardgrass		4.9 (0.1)	10.0 (0.6)	
		Soybeans				2.2 (0.1)
	3	Rye		10.7 (0.5)		
		Corn			3.8 (0.4)	
		Soybean				2.2 (0.1)
	4	Corn			5.0 (0.5)	
		Soybean				1.2 (0.05)

Figure legends

Figure 1. The density of Canada thistle (*C. arvensis*) in four cropping systems that differed in crop rotation and tillage frequency at the initiation (Year 0) and in year three of a four-year organic feed and forage cropping systems experiment near Rock Springs, PA. * indicate significant ($P < 0.05$) reductions in *C. arvensis* density between Year 0 and Year 3 within a system. Data are least squares means, $n = 8$. Error bars represent standard errors.

Figure 2. Weed biomass (annual and perennial) in four cropping systems that differed in crop rotation and tillage frequency during a soybean uniformity trial at the end of a four-year organic feed and forage cropping systems experiment near Rock Springs, PA. Data are least squares means, $n = 8$. Different letters represent significant differences between systems ($P < 0.05$). Error bars represent standard errors.

Figure 3. Soybean grain yields in a uniformity trial conducted in four cropping systems that differed in crop rotation and tillage frequency near Rock Springs, PA. Data are least squares means, $n = 8$. Different letters represent significant differences between systems ($P < 0.05$). Error bars represent standard errors.

Figure 4. Permanganate oxidizable carbon (POXC) in four cropping systems that differed in crop rotation and tillage frequency sampled in late season (Sept/Oct) of each year in a four-year organic feed and forage cropping systems experiment near Rock Springs, PA. Systems 1 and 3 had a legacy of reduced tillage at the onset of the experiment relative to Systems 2 and 4. Data are least squares means, $n = 8$. Different letters represent significant differences between systems within each year ($P < 0.05$). Error bars represent standard errors.

Figure 5. Nitrogen in aboveground biomass of non-nodulating soybean planted in subplots in four cropping systems that differed in crop rotation and tillage frequency at the end of a four-year organic feed and forage cropping systems experiment near Rock Springs, PA. Data are least squares means, $n = 8$. Different letters represent significant differences between systems ($P < 0.05$). Error bars represent standard errors.

Figure 6. Least squares mean activity-densities of generalist predatory arthropods (Araneae, Opiliones, Carabidae, Staphylinidae, and Chilopoda) across four cropping systems that differed in crop rotation and tillage frequency over a 4-year organic feed and forage cropping systems experiment near Rock Springs, PA. Different letters represent significant differences between systems within each year ($P < 0.05$). Error bars represent standard errors ($n = 8$).

Figure 7. Annual cash flows and cumulative net present values (NPV) for four cropping systems that differed in crop rotation and tillage frequency over a four-year organic feed and forage cropping systems experiment, including the establishment year, near Rock Springs, PA. Data are least squares means, $n = 6$. Error bars represent standard errors of high, medium and low price scenarios.