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Legacy effects of contrasting organic grain cropping systems on soil health indicators, soil invertebrates, weeds, and crop yield

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ABSTRACT

Elucidating relationships between the soil food web, soil processes, and agroecosystem function is a critical step toward a more sustainable agriculture. Soil and crop management practices can alter these relationships, and their effects can persist even after imposing new management practices. In 2005, the Cornell Organic Grain Cropping Systems Experiment was established in central New York. Four cropping systems that varied in fertilizer inputs, tillage practices, and weed control were compared: High Fertility, Low Fertility, Enhanced Weed Management, Reduced Tillage. Two crop rotation entry points were included in the experiment. In June 2017, the entire experimental site (plots and alleyways) was plowed and seeded with sorghum sudangrass [*Sorghum bicolor* (L.) Moench x *S. sudanense* (Piper) Stapf] as part of a uniformity trial to assess legacy effects of past management practices. Prior to initiating the uniformity trial, soil samples were collected and analyzed for soil health indicators. Soil samples were also collected to assess soil invertebrate abundance and community structure 34 and 70 days after planting. Sorghum sudangrass and weed biomass were sampled at the end of the uniformity trial in September 2017. Legacy effects of past management that were observed during the uniformity trial were associated with differences in nutrient inputs and soil disturbance, as well as the preceding crop. The High Fertility system had greater soil phosphorus than the Low Fertility system, and in one of the two crop rotation entry points, soil aggregate stability and soil respiration were greater in the Reduced Tillage system compared to the Enhanced Weed Management system. The Enhanced Weed Management cropping system also had a soil invertebrate community characterized by more disturbance tolerant taxa. Weed biomass varied by crop rotation entry point, but not cropping system. Sorghum sudangrass biomass was greater in the Reduced Tillage system than the Low Fertility system, and the entry point that had greater weed biomass also had greater sorghum sudangrass biomass. Piecewise structural equation modelling (SEM) was used to test relationships between response variables and showed that soil phosphorus, soil aggregate stability, and soil respiration explained variation in abundance of some invertebrates, and that aggregate stability, soil respiration, soil moisture, weed biomass, and a select group of invertebrates affected sorghum sudangrass biomass production. Overall our findings show that soil invertebrates can mediate the relationship between soil health indicators and crop productivity, and provide support for including direct measurements of soil invertebrates in soil health assessments.

1. Introduction

In addition to water, light, and temperature, crop productivity is determined in large part by soil chemical, physical, and biological properties. For instance, soil nutrient content influences crop growth rate and nutrient uptake, while pH modifies crop nutrient acquisition (Bedada et al., 2014; Gosal et al., 2018). Similarly soil physical properties including soil aggregation, bulk density, and available water capacity affect root growth, biomass accrual, and plant water availability (Mann et al., 2010; Zaki et al., 2018). In unmanaged ecosystems, the soil's biota are important determinants of nutrient supply and soil tilth, and thus, contribute to plant production dynamics. Through their direct interactions with plants, soil biota also exert additional influence on plant productivity and alter a crop's capacity to resist, compete with, or recover from stressors (Yang et al., 2018).

Despite awareness among farmers of the many linkages between

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plant productivity and soil biogeochemical traits, the ability to manage complex soil biological processes for the purpose of optimizing crop yield in agricultural systems remains limited. Many conventional agricultural management practices suppress key biota and soil biological processes (Alvarez and Steinbach, 2009), and in some cases management practices aimed specifically at improving soil physical and biological properties, such as reduced tillage, lead to reduced crop yields (Larsen et al., 2014; Ryan and Peigné, 2017; Smith et al., 2011). Such tradeoffs can complicate management recommendations and lead to confusion among farmers interested in managing for both crop productivity and soil health, which is recognized as the capacity of a soil to function as its own system that maintains ecological processes (Rai et al., 2011).

Tradeoffs between soil health and crop yield may be particularly significant under organic production practices. Organic systems are fundamentally different from conventional cropping systems in that organic farmers "must manage soil fertility, including tillage and cultivation practices, in a manner that maintains or improves the physical, chemical, and biological condition of the soil and minimizes soil erosion" ("National Organic Program," 2000). The focus on maintaining overall soil health in organic systems stems from the elevated importance of soil biological processes in supporting crop protection and productivity.

Unlike conventional systems that rely on synthetic fertilizers and plant protectants, organic cropping systems depend heavily upon the activity of decomposers to convert organic matter amendments to plant-available nutrient forms. Restrictions on synthetic pesticides in organic systems also increase reliance on the activities of naturally occurring microbes and invertebrates to enhance plant stress tolerance and suppress crop insect pests, pathogens, and weeds (Jerkins and Ory, 2016). Soil invertebrates, a specific group of biota which include a taxonomically diverse array of arthropods, including collembola and mites, have been shown to contribute to both of these ecosystem services. Soil invertebrates increase nutrient cycling in organic systems and enhance the functioning of soil food webs (Cao et al., 2011a; Wolters, 2000). Additionally, soil invertebrates likely play an important role in plant pathogen and insect pest control in agroecosystems (Lavelle et al., 2006, 2004). Although the general importance of these soil biological processes in maintaining plant health and productivity in organic cropping systems is widely recognized, knowledge and tools for optimizing these processes are still limited, and many organic producers currently rely on soil cultivation as an alternative to conventional herbicides and other means of pest management (Armengot et al., 2015; Baker and Mohler, 2015; Peigné et al., 2007).

Organic farmers have an array of options for managing soil structure, fertility, and weeds, including crop rotations, high density planting, multiple tillage options, cover crops, organic amendments and fertilizers, and pesticides that are approved for certified organic production (Baker and Mohler, 2015; Melander et al., 2005; Watson et al., 2006). Although the impacts of many of these management practices on agricultural services and disservices have been examined in previous studies, their combined effects when implemented as a system on soil health and crop productivity are still poorly understood. This is particularly true when attempting to characterize the long-term nature of plant-soil feedbacks (Ehrenfeld et al., 2005).

Long-term cropping systems experiments are particularly useful for evaluating the combined effects of different management practices and can provide valuable insights into system optimization (Giuliano et al., 2016), for example in areas such as soil nutrient cycling and retention (Dao et al., 2015; Drinkwater et al., 1998). Following long-term experiments, uniformity trials are a useful tool for evaluating the cumulative effect of management practices on agroecosystem functioning. Although approaches to implementing a uniformity trial can vary, it is typical that a crop is grown using identical management across the entire experimental area to evaluate the legacy effects of past management practices (Jernigan et al., 2017; Teasdale et al., 2007).

The Cornell Organic Grains Cropping Systems Experiment (OGCS) was established in 2005 to compare four organic systems characterized by different tillage, fertilizer, and weed management practices. In 2017, a uniformity trial was conducted to evaluate the legacy effects of these management practices. We tested for differences in traditional soil health indicators, soil invertebrates, weed abundance, and crop productivity among the four organic cropping systems. Although many studies also use traditional soil health measurements such as soil organic matter content, microbial biomass, and respiration as proxies for the amount and activity of soil organisms, we also chose to include direct measurement of soil animal abundance and composition to evaluate their strength as predictors of crop productivity (Roper et al., 2017). Soil invertebrates are good indicators of changes in soil health because they are affected by chemical, physical, and biological properties of soil, contribute directly and indirectly to many soil ecosystem services, and are highly sensitive to agricultural management practices (Aspetti et al., 2010; Barbercheck et al., 2019; Bedano et al., 2016; Ekschmitt et al., 2001; George et al., 2017; Lavelle et al., 2006; Menta et al., 2008). In addition to quantifying differences among cropping systems, we hypothesized that 1) crop yield would be positively influenced by soil health indicators and soil invertebrates, and negatively influenced by weeds; 2) soil invertebrates would be positively influenced by both soil health indicators and weeds; and 3) weeds would be positively influenced by soil health indicators (Fig. 1).

2. Materials and methods

2.1. Study site and experimental design

The OGCS experiment was established in 2005 at the Musgrave Research Farm near Aurora, NY (42.73 °N, 76.65 °W). The soil type at the site is a moderately well-drained, calcareous Lima silt loam (fine-loamy, mixed, semiactive, mesic Oxyaquic Hapludalf), with partial subsurface tile drainage. The experimental site is located in USDA Plant

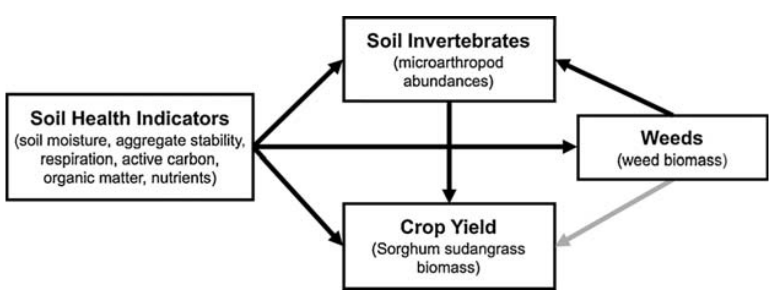

Fig. 1. Hypothesized model of how soil health indicators, soil invertebrates (microarthropods), and aboveground weed biomass effect sorghum sudangrass biomass. Black arrows indicate positive relationships. Grey arrows indicate negative relationships.

Table 1
Management practices summary for cropping systems from 2010–2017.

System	High Fertility (HF)	Low Fertility (LF)	Enhanced Weed Management (EWM)	Reduced Tillage (RT)
Crop rotation	C/r-S-SP-B/BU-S-SP/c	C-S-SP/c	C-S-SP/c	C-S-SP-B/BU-S-SP/op
Fertility Inputs[a]				
Compost[b] (Mg ha^{-1})	3.4 (B), 1.1 (SP)		1.1 (SP)	3.4 (B), < 2 (C)
P, K[c]	varied (C, SP)			
Tillage[d]				
Moldboard plow	C, S, SP, B, BU	C, S	C, S, SP	
False seedbed			S (if possible)	
Deep zone till				C
Chisel plow				S, SP, B, BU
Weed control[e]				
Tine harrow	1–3	1–3	1–3	
Inter-row cultivator	1–4	1–4	2–5	1–3

C corn (*Zea mays* L.), S soybean (*Glycine max* L. Merr.), SP spelt (*Triticum spelta* L.), B winter barley (*Hordeum vulgare* L.), BU buckwheat (*Fagopyrum esculentum* L.); r annual ryegrass (*Lolium multiflorum* L.), c red clover (*Trifolium pratense* L.), op oat (*Avena sativa* L.)/Austrian winter pea (*Pisum sativum* L.) mix.

[a] Application rates per season. All systems received a small amount of composted poultry manure as a starter fertilizer before corn, whereas LF also received potassium sulfate as a starter fertilizer.

[b] Composted poultry manure (5-5-3 N-P_2O_5-K_2O, Kreher's Enterprises, Clarence, NY, USA). Rates assume 14% moisture. EWM did not receive compost before 2011. RT received variable compost when necessary to supplement inadequate legume N.

[c] Organic fertilizers applied based on P and K soil tests.

[d] Tillage practices by crop. All systems also used secondary tillage (disc, roller harrow).

[e] Events per season in corn and soybean.

Hardiness Zone 6A with an average annual precipitation of 919 mm. During the uniformity trial from June 29, 2017 to September 10, 2017, rainfall was 258 mm, very wet conditions, and growing degree day accumulation was 719 (base 10 °C) (NYS IMP Program, C.U., 2019). The experiment used a split-plot randomized complete block design with four replications. The main plots were four different cropping systems that represented four management strategies: High Fertility (HF), Low Fertility (LF), Enhanced Weed Management (EWM), and Reduced Tillage (RT) (Tables 1 and 2). Split plots ($n = 32$) consisted of two entry points into the crop rotation so that the same crop in the rotation was grown in two successive years in adjacent subplots. Cropping system studies (Davis et al., 2012; Ryan et al., 2010; Smith et al., 2008) commonly use multiple entry points into the crop rotation to account for the effects of weather on crop production and ecological processes. The cropping system subplots were 9.1 m by 30.5 m to accommodate field-scale equipment. Additional details of the experiment and cropping system management can be found in manuscripts published by Caldwell et al. (2014) and Ball et al. (Ball et al., 2019).

Table 2
Summary of the number of tillage events in each cropping system.from 2005 to 2017.

	Entry Point A				Entry Point B			
	High Fertility	Low Fertility	Enhanced Weed Management	Reduced Tillage	High Fertility	Low Fertility	Enhanced Weed Management	Reduced Tillage
Primary tillage								
Moldboard plow	11	9	12	2	14	10	13	2
Chisel plow	1	0	0	8	0	0	2	9
Zone builder	0	0	0	2	0	0	0	1
Sum	**12**	**9**	**12**	**12**	**14**	**10**	**15**	**12**
align = "center" Secondary tillage								
Disc	13	13	13	9	12	12	10	9
Field cultivator	7	0	1	11	2	2	8	4
Scrape ridges	0	0	0	4	0	0	0	7
Sum	**20**	**13**	**14**	**24**	**14**	**14**	**18**	**20**
align = "center" Shallow tillage								
Rotary hoe	1	3	3	0	0	0	0	0
Tine weed	10	11	11	4	10	11	12	2
Cultivate	20	18	25	18	21	21	28	24
Roller harrow	14	13	14	8	14	12	14	9
Sum	**45**	**45**	**53**	**30**	**45**	**44**	**54**	**35**
align = "center" Cumulative Total	77	67	79	66	73	68	87	67

2.2. Cropping systems

The four cropping systems varied in crop rotations, fertilizer inputs, tillage practices, and weed control throughout the long-term experiment. Specific management practices used in the experiment were based on discussions with, and recommendations from, a dedicated advisory board of experienced organic farmers in the region. The management practices used in the experiment were either common practices used by farmers on the advisory board or were new practices that the farmers were interested in exploring. The crops were chosen based on crops commonly grown in the region. In 2011, after completing two 3-yr rotations, management practices were modified to address specific concerns that had arisen in each system. The cropping system management practices from 2011 to 2017 are summarized in Table 1. The long-term experiment followed a 3-yr soybean (*Glycine max* L. Merr.)→spelt (*Triticum spelta* L.)/red clover (*Trifolium pratense* L.)→corn (*Zea mays* L.) crop rotation, with two exceptions: (1) the RT system established the cover crop winter pea (*Pisum sativum* L.) after spelt, instead of overseeding the cover crop red clover into spelt as was done in the other systems, in order to allow for cover crop termination without intensive tillage, and (2) the HF and RT systems planted buckwheat (*Fagopyrum esculentum* L.) and barley (*Hordeum vulgare* L.) instead of corn at one point in the rotation from 2011 to 2017.

The HF cropping system used soil fertility inputs based on common organic farming practices. Corn was fertilized with a red clover green manure plus starter fertilizer (336-526 kg ha^{-1} of 5-4-3; 4.5-3.5-11) starting in 2010. From 2005–2010, an application of 2 Mg ha^{-1} of composted poultry manure with a nutrient composition of 5-5-3 was also applied. The cover crop annual ryegrass (*Lolium multiflorum* L.) was overseeded into HF corn at final cultivation. Soybean and spelt were fertilized with compost and commercial organic fertilizers approximated by the chemical fertilizer rates recommended in the Cornell Guide for Integrated Field Crop Management (Cornell Cooperative Extension, 2012). Barley was fertilized with composted poultry manure (approximately 3600 kg ha^{-1}). Tillage for all crops was done with a moldboard plow, disc harrow or field cultivator, and roller harrow.

The LF cropping system incorporated minimal fertility inputs to reduce production cost. Fertilizer in the LF system consisted of a red clover green manure and the application of starter fertilizer as per HF through the planter for corn. The LF system also received K_2SO_4 fertilizer (approximately 3.4 kg ha^{-1} of 0-0-51) in addition to the starter fertilizer for corn after 2009. The LF system used the same tillage operations as the HF system.

The EWM cropping system simulated a farm that focuses on weed management to enhance crop production. The EWM system received starter fertilizer as per HF, and after 2011, approximately 1200 kg ha^{-1} of composted poultry manure. The cover crop annual ryegrass was overseeded into EWM corn at final cultivation. This system used additional tillage and cultivation in corn and soybean when these seemed likely to improve weed control, with at least one of the extra cultivations employing a belly-mounted rather than a rear-mounted cultivator for greater precision. The EWM system moldboard plowed and disked the soil rather than disking alone before planting spelt. Spelt was seeded at a 30 to 50% greater rate than the other systems to enhance weed suppression by increasing crop competition from 2005-2011. During the last six years of the experiment, after 2011, all four cropping systems seeded spelt at the increased rate to help with weed suppression.

The RT cropping system focused on improving soil health by using less intensive tillage than the other cropping systems. Soil disturbance was decreased with the use of ridge tillage and chisel plowing. The RT system received starter fertilizer as per HF, plus 5-5-3 compost at lower rates to supply sufficient N to compensate for inadequate legume stands. Barley was fertilized with composted poultry manure (approximately 3600 kg ha^{-1}). Tillage before barley and buckwheat planting utilized a chisel plow and disk, followed by a roller harrow.

The cumulative number of tillage events that occurred in each cropping system varied between crop rotation entry points due to weather, weed pressure, and year to year variability in field conditions (Table 2). Although moldboard plow and chisel plow tillage are different in terms of tillage intensity, a roughly similar number of primary tillage events occurred in all systems over the duration of this experiment. The RT system had the greatest number of secondary tillage events in both crop rotation entry points, which can be attributed to the years when ridge tillage, and thus ridge scraping, was used in this system (Table 2). The EWM system had the greatest number of shallow tillage events in both crop rotation entry points due to the focus on weed management in the system (Table 2).

Alleyways between each experimental block measured 9 x 98 m, and were not tilled since the experiment was initiated in 2005. Alleyways were used for driving vehicles (i.e., tractors and lab trucks) between blocks for management operations and sample collection. Grass was mowed in the alleyways periodically throughout the summer to aid in sampling and field operation efficiency. Dominant plant species in the alleyways prior to the uniformity trial were *Plantago major* L. (broadleaf plantain), *Taraxacum officinale* G.H. Weber ex Wiggers (dandelion), *Oxalis stricta* L. (yellow wood sorrel), *Poa pratensis* L. (Kentucky bluegrass), and *Poa annua* L. (annual bluegrass).

In 2017, after the cropping systems had been in place for 12 years, a uniformity trial was conducted. Annual ryegrass was the last crop planted in entry point A. Red clover was the last crop planted in entry point B, with the exception of the RT system, which was planted with winter pea. The experiment area was moldboard plowed to a depth of 10 to 15 cm on June 26, 2017, then disked and harrowed on June 28, 2017 to prepare the soil for planting. Shallow moldboard plow tillage was used to standardize the seedbed and reduce effects of residue from the previous crop, which varied by cropping system and entry point. On June 29, 2017, sorghum sudangrass was planted in all plots at a rate of 48.2 kg ha^{-1} to a depth of 1.9 to 2.5 cm on 19-cm rows. The sorghum sudangrass received no fertilizer inputs or further management before biomass sampling and termination on September 10, 2017. Sorghum sudangrass was used for this uniformity trial because it had not previously been grown during the long-term experiment and because of its sensitivity to soil nutrient levels, use as a phytometer in other research, and increasing importance as a forage crop in the Northeastern United States (Hodgdon et al., 2016; Ketterings et al., 2007).

2.3. Data collection

2.3.1. Soil health indicators

Soil samples were collected for soil health analyses on May 24, 2017. One random sample was taken in each of the NE, SE, NW, and SW quadrats of each plot to create a composite sample for analysis. Root crowns were avoided when sampling the soil. Soil was sampled using a 10.8 cm diameter golf corer to a depth of 20 cm. Soil samples for each plot were thoroughly mixed and rocks larger than approximately 4 cm diameter were removed. One composite soil sample comprised of four cores was also collected in each of the alleyway areas to the south of each block to compare to samples from the treatment plots.

Wet soil weights and rock weights were collected in field. Soil was stored in plastic bags in a cooler until processing. Soil samples were processed for wet aggregate stability, respiration, and active carbon by the Cornell Soil Health Lab following the standard operating procedures for the Cornell Comprehensive Assessment of Soil Health (Moebius-Clune et al., 2016). Soil aggregate stability was measured using a wet sieving technique to determine the percent of stable aggregates (Moebius et al., 2007). Soil respiration was measured by quantifying the amount of carbon dioxide (CO_2) produced during a four-day incubation (Bottomley et al., 1994). Active carbon was measured using a spectrophotometer to quantify potassium permanganate oxidation (Islam et al., 2003). Soil samples were analyzed for organic matter content and soil nutrients by Dairy One soil testing lab. Soil organic matter percentage was measured using a loss on ignition protocol (Broadbent, 1965), and soil nutrient analyses were conducted using a standard Mehlich 3 soil nutrient extraction (Mehlich, 1984).

2.3.2. Soil invertebrates

Soil was sampled on August 1, 2017 (Date 1–34 days after planting) after the sorghum sudangrass was established, and again on September 6, 2017 (Date 2–70 days after planting). These two sampling dates were selected to capture the seasonal trends in invertebrate abundance. Ten soil cores were collected in each plot using a 1.75 cm diameter soil fertility probe to a depth of 10 cm. Invertebrate sampling specifically targeted microarthropods and other small invertebrate taxa, and the size of the soil cores was selected to allow for more cores to be taken throughout each plot to capture the invertebrate community and abundance in each plot, due to the varying abundance of invertebrates within soils. Soil samples were also collected in the alleyway area to the south of each block. Samples were taken at the ends and turns of two parallel "W" shapes down the length of each plot. Plot variations (e.g. wet spots) were not avoided during sample collection. Areas within 1.8 m of a plot edge were avoided when sampling. All ten cores from each plot were combined in plastic bags and placed in a cooler. Within 24 h of soil sample collection, each composite soil sample for each plot was placed on a modified Berlese funnel for invertebrate extraction. Over the course of the 3-day extraction, temperature was gradually increased from 30 °C to 50 °C. Invertebrates were extracted into 75% ethanol, then were topped off with 95% ethanol and stored until the samples were processed. In this study invertebrates include mites, collembola, and other taxa within Arthropoda. Extracted invertebrates were identified to family using keys published by Borror and DeLong, Dindal, and Krantz (Borror and DeLong, 1964; Dindal, 1990; Krantz et al., 2009). After the soil samples were removed from the Berlese funnels, soil mass loss was determined from the air-dried weights of the soil samples. All arthropod abundances are reported as the number of individuals kg^{-1} dry soil.

2.3.3. Crop and weed biomass in the uniformity trial

Sorghum sudangrass and weed biomass were sampled using two 0.5-m^2 quadrats per plot on August 31, 2017 and September 1, 2017. Quadrats were placed in the north and south halves of each plot, avoiding areas with abnormal sorghum sudangrass growth due to planting equipment issues. Sorghum sudangrass and weed biomass were also sampled in the alleyway area to the south of each block, except for the Block 4 alleyway area where sorghum sudangrass was not planted. Weeds were identified to species. Crop and weed biomass were clipped at ground level, dried at 60 °C for 72 h, and then weighed.

2.4. Data analysis

For univariate analyses, we used analysis of variance (ANOVA) to test for differences in each of the soil health indicators, total invertebrate abundance, and plant biomass data using the *lmer* function in the 'lme4' package in R version 3.4.2 (R core team, 2017). Cropping system, entry point, and their interaction were included as fixed effects, and a random cropping system nested in block effect was included. No alleyway data were included in any ANOVAs. Plant biomass, sorghum sudangrass biomass, weed biomass, active carbon, and organic matter data were transformed as $\ln(x + 1)$ to meet the assumptions of normality and homoscedasticity for the ANOVAs. Date 1 and Date 2 invertebrate data were square root transformed to meet the assumptions of normality and homoscedasticity for the ANOVAs. Pairwise mean comparisons were made by using Fisher's LSD method, and significance was declared for $P \leq 0.05$. We chose to interpret P-values that rounded down to 0.05 given the ecological and economic impacts of the differences observed in those metrics (aggregate stability and sorghum sudangrass biomass). Back transformed means are presented in the tables and text.

Alleyway means were compared to the cropping system means, entry point means, and the system x entry point interaction means using two sample t-tests. This approach was used because the alleyways were not formal treatments spatially randomized as part of the experiment, but rather adjacent reference points included in the uniformity trial because of the comparison value they provide.

For multivariate analyses, the significance of cropping system, entry point, and their interaction was tested on the square root transformed Date 1 and Date 2 invertebrate data, and the $\ln(x+1)$ transformed weed biomass data with a permutation-based multivariate ANOVA (Anderson, 2001) using the *Adonis2* function of the 'Vegan' package (Oksanen et al., 2010) in R software (R core team, 2017). Pairwise comparisons were made using the *pairwise.adonis* wrapper function of the 'Vegan' package (Martinez Arbizu, 2019) in R software (R core team, 2017) with a Bonferroni adjustment. Date 2 invertebrate data and the weed biomass data were both then subjected to nonmetric multidimensional scaling (NMDS) with Bray-Curtis distance metric implemented in the 'Vegan' package. Datasets for the permutation-based multivariate ANOVAs and NMDS had taxa occurring in less than 5% of plots removed. No alleyway data was included in the permutation-based ANOVAs or pairwise comparisons, however the alleyway data was included in the NMDS to compare their community structure to those of the cropping systems.

We used PC-ORD 6 (MjM Software Design, Gleneden Beach, OR) to conduct an indicator species analysis (Dufrene and Legendre, 1997) to test for associations (based on abundance and frequency of occurrence) between the invertebrate taxa collected at each sampling date and the four cropping systems and the alleyway. We also conducted an indicator species analysis on the weed biomass data using the same procedure. Indicator values for each species in each system were calculated by multiplying the relative abundance of the species within a cropping system by the relative frequency within a cropping system. Indicator values range from 0 (no association) to 100 (exclusive association with one system). For example, if 80% of all of the dandelion in the experiment was found in the RT system (relative abundance), and within the RT system dandelion was found in 3 of the 4 blocks (relatively frequency), then the indicator value for dandelion in the RT system would be 60 (i.e., 80% x 75% = 60). Significance of indicator values was assessed using a Monte Carlo procedure (1000 simulations).

We used piecewise structural equation models (SEMs) to test our hypothesis that crop productivity would be affected by soil health indicators, soil invertebrates, and weed abundance. The piecewise SEM method, a modelling approach based on linear regressions, was chosen to give more statistical power to the model due to the small sample size ($n = 35$). All the data used in the SEM were transformed for normality as with the ANOVAs. All variables included in the modelling were continuous and there were no missing data.

Exploratory factor analysis (EFA) followed by confirmatory factor analysis (CFA) was used on the Date 2 invertebrate data to determine which taxa to include in the model. This method identified groups of invertebrates that responded similarly to their environment over the course of the long-term experiment (Kozan and Richardson, 2014). Date 2 invertebrate data was used in the SEM, instead of the Date 1 invertebrate data, since this data was collected closer to the sorghum sudangrass biomass harvest. This process was also used on the weed biomass data. The taxa groups identified from the EFA and CFA were summed to create representative response groups of invertebrates and weeds for the piecewise SEMs (i.e. FaunaF1, FaunaF2, WeedsF1). The taxa groups were summed, instead of incorporated into latent variables, in the model due to piecewise SEM being unable to accommodate latent

Table 3
Significance levels from the ANOVAs performed on the soil health indicators with means (P < 0.05, bolded). Means with the same letters are not significantly different (Fisher's LSD, P > 0.05). Upper case and lower case letters indicate that separate mean comparisons were conducted. Means that are significantly different from the alleyway mean for each soil health indicator are marked with an asterisk.

	Surface Soil Moisture %	Aggregate Stability %	Respiration mg CO_2 g^{-1} dry wt soil	Active Carbon ppm	Organic Matter %	pH	Nitrate ppm	Phosphorus ppm	Potassium ppm
P-Value									
System	**0.013**	**0.025**	**0.014**	0.573	0.426	0.804	0.597	**0.010**	0.283
Entry Point	0.301	0.884	**0.019**	0.098	0.724	0.275	0.530	**0.009**	0.445
System x Entry Point	0.689	**0.052**	**0.003**	0.200	**0.044**	0.358	0.782	0.852	0.206
System									
High Fertility	21.3	**B** 25.3*	**B** 0.66	531	3.03*	7.66	15.8	9.50	**A** 60.0
Low Fertility	22.8	**AB** 26.0*	**B** 0.63	550	3.17	7.65	17.3	4.75	**B** 49.9*
Enhanced Weed Management	21.8	**B** 26.4*	**B** 0.60	527	3.06*	7.64	17.9	4.75	**B** 55.9
Reduced Tillage	24.5	**A** 33.8	**A** 0.71	535	3.24	7.52	18.1	9.38	**A** 60.6
Entry Point									
A	23.0	28.0	0.63	530	3.11*	7.68	16.9	6.31	**b** 54.9
B	22.2	27.7*	0.68	542	3.14	7.57	17.6	7.88	**a** 58.3
Interaction									
Entry Point A									
High Fertility	21.8	26.1*	**B** 0.68	**A** 538	3.21	**A** 7.85	16.3	8.75	65.3
Low Fertility	22.5	25.6	**B** 0.53*	**B** 536	3.02	**A** 7.56	16.8	4.00*	48.0*
Enhanced Weed Management	22.7	22.3*	**B** 0.58	**B** 517	3.03	**A** 7.68	17.0	4.25*	54.0
Reduced Tillage	24.8	38.2	**A** 0.73	**A** 528	3.19	**A** 7.63	17.8	8.25	52.5
Entry Point B									
High Fertility	20.8	24.6*	**a** 0.65	**ab** 524	2.85*	**b** 7.47	15.3	10.25	54.8
Low Fertility	23.1	26.3*	**a** 0.73	**a** 564	3.34	**a** 7.74	17.8	5.50	51.8*
Enhanced Weed Management	20.8	30.6	**a** 0.63	**b** 537	3.10	**ab** 7.60	18.8	5.25	57.8
Reduced Tillage	24.1	29.4	**a** 0.70	**ab** 542	3.29	**a** 7.42	18.5	10.50	68.8
Alleyway Means	24.7	33.9	0.75	532	3.45	7.57	17.0	7.25	70.8

variables. Correlation analysis and partial least square regression were conducted using each community data set and the soil health indicators to determine which soil health indicators had the most significant relationships with the invertebrate and weed communities. Based on these analyses, the hypothesized *a priori* SEM included four soil health indicators, two invertebrate groups, two weed groups, and sorghum sudangrass biomass (Fig. 1).

Sorghum sudangrass biomass, the two invertebrate community groups, and the two weed community groups were assessed individually using linear mixed effects models using the *nlme* package for the SEM (Pinheiro et al., 2015). The soil health indicators, invertebrate community groups, and weed community groups were included as fixed effects for the sorghum sudangrass model. The soil health indicators and weed community groups were included as fixed effects for the invertebrate community group models. The soil health indicators were the fixed effects included in the weed community group models. Cropping system nested in block was included as a random effect in each model. The fixed effects included in each linear mixed effect model was determined based on the timing of the field sampling.

Prior to the analysis of the full SEM, we dropped non-significant (P > 0.1) predictor/response variables (WeedsF2) from the model to preserve degrees of freedom. We then subjected our hypothesized diagram to a test of directed separation and evaluated the SEM with Fisher's *C* statistic produced by the *piecewiseSEM* package (Lefcheck, 2016). To evaluate our hypothesis, we obtained the standardized regression coefficients and p-values for path coefficients to determine the directionality and relative strength of explanatory variables, as implemented in recent ecological research (Fan et al., 2016; Wallace, 2018). Marginal R^2 values report the variance explained by the fixed factors, and conditional R^2 values report the variance explained by the fixed factors plus random factors.

3. Results

3.1. Soil health indicators

Chemical, physical, and biological soil health indicators were measured to determine the effects of previous management practices (Table 3). Soil phosphorus in individual plots and alleyways (n = 32 plots + 4 alleyways) ranged from 2.8 ppm to 15.9 ppm. Phosphorus varied by cropping system (P = 0.009) and crop rotation entry point (P = 0.009) (Table 3). The RT and HF systems had greater plant available soil phosphorus compared to the LF and EWM systems.

Soil wet aggregate stability measurements in individual plots and alleyways (n = 32 plots + 4 alleyways) ranged from 17.7% to 49.8%. Greater wet aggregate stability percentages indicate a greater proportion of total soil aggregates that are resistant to degradation during a rainfall event. Soil wet aggregate stability had significant cropping system and crop rotation entry point interaction effects (P = 0.052) (Table 3). Within entry point A, the RT system had greater soil aggregate stability than the three other cropping systems. Surface soil moisture was affected by cropping system (P = 0.013) (Table 3). The RT system had a greater surface soil water content on a mass basis than the HF and EWM systems. Soil organic matter varied by the cropping system and crop rotation entry point interaction (P = 0.044) (Table 3). Within entry point B, the RT and LF systems had greater organic matter

Table 4
Significance levels from the ANOVAs performed on the soil invertebrates from the Date 1 and Date 2 sampling with means ($P < 0.05$, bolded). Means with the same letters are not significantly different (Fisher's LSD, $P > 0.05$). Upper case and lower case letters indicate that separate mean comparisons were conducted. Means that are significantly different from the alleyway mean for each invertebrate group are marked with an asterisk. Soil invertebrate units are # invertebrates Kg^{-1} soil.

	Date 1 Sampling					Date 2 Sampling					
	Onychiuridae	Isotomidae	Histiostomatidae	Phoretic Hypopi	Carabid Beetle Larva	Total Invertebrates	Histiostomatidae	Microdispidae	Scutacaridae	Phoretic Hypopi	Acaridae
P-Value											
System	0.384	0.463	0.23	**0.003**	0.621	0.355	0.838	0.33	0.078	**0.024**	0.33
Entry Point	0.664	0.286	**0.043**	0.202	0.34	0.163	0.989	0.221	0.845	0.675	0.691
System x Entry Point	0.856	0.132	0.082	0.644	**0.025**	**0.006**	0.592	0.845	0.387	0.098	**0.014**
System											
High Fertility	7.53	0.45	2.73	0.68 **B**	0	138.3	3.05	2.56	5.02	45.51 **B**	7.6
Low Fertility	1.51*	< 0.0001	3.64	1.49 **B**	0.88	155	5.14	2.28	2.37	72.24 **AB**	5.2
Enhanced Weed Management	2.30*	0.88	0.15	9.33 **A**	0.4	257.6	1.87*	1.45	0.67*	140.13 **A**	23.3
Reduced Tillage	4.83	0.15	0.63	0.4 **B**	0.31	189.7	3.43	6.37	23.43	25.08 **B**	7.59
Entry Point											
A	3.22*	0.44*	0.64 **B**	1.3	0.3	167.2	3.25	4.14	6	59.6	10.89
B	4.19*	0.11	2.47 **A**	2.99	0.76	198.4	3.29*	1.91	5.15	81.88	9.06
Interaction											
Entry Point A											
High Fertility	5.24	1.79	0.3	0.3	0 **A**	148.3 **AB**	1.57	3.56	1.77	53.1	11.85 **AB**
Low Fertility	0.91*	< 0.0001	2.48	0.27	0.27 **A**	91.3 **B**	9.32	2.28	3.03	23.53	1.64 **B**
Enhanced Weed Management	2.57	1.77	< 0.0001	7.41	< 0.0001 **A**	211.5 **AB**	1.22	3.45	0.3	101.54	12.22 **AB**
Reduced Tillage	5.45	< 0.0001	1.19	0.58	1.23 **A**	238.7 **A**	3.26	8.32*	38.28	24	24.82 **A**
Entry Point B											
High Fertility	10.22	< 0.0001	7.61	1.23	0 **b**	128.6 **b**	5.03	1.72	9.93	24.08	4.29 **b**
Low Fertility	2.27	0	5.03	3.66	1.83 **a**	235.3 **ab**	2.19	2.29	1.78	104.4	10.78 **ab**
Enhanced Weed Management	2.03	0.3	0.6	11.47	1.6 **a**	308.2 **a**	2.67*	0.3	1.20*	137.18	37.92 **a**
Reduced Tillage	4.24	0.58	0.26	0.26	< 0.0001 **b**	146.4 **ab**	3.60*	4.67	12.2	5.21	0.28 **b**
Alleyway Means	15.92	0	4.35	9.45	0.31	238.2	9.18	2.66	12.56	44.3	4.3

Table 5
Indicator species analysis results showing the soil invertebrate taxa that were associated with a cropping system at both sampling dates (P < 0.05, bolded) (P < 0.1, italicized).

Data	Invertebrate Taxa	Cropping System	Observed Indicator Value	Mean	S. Dev	P-value
Date 1	Onychiuridae	Alleyway	40.4	24.6	5.46	**0.010**
	Phoretic Hypopi	Alleyway	33.8	23.6	6.99	*0.091*
	Rhodacaridae	High Fertility	34.7	25.5	6.08	*0.088*
	Acaridae	Alleyway	34.2	21.7	8.14	*0.088*
	Tectocepheidae	Alleyway	35.6	16.7	8.36	**0.029**
Date 2	Onychiuridae	Alleyway	34.3	29.0	3.81	*0.092*
	Isotomidae	Alleyway	35.7	26.8	6.57	*0.094*
	Scutacaridae	Reduced Tillage	59.2	42.8	11.23	*0.065*
	Phoretic Hypopi	Enhanced Weed Management	40.6	30.2	5.73	*0.056*
	Rhodacaridae	Alleyway	31.2	26.7	2.98	0.082
	Carabid Beetle Larva	Alleyway	49.7	15.9	8.30	**0.009**

than the HF system. Soil respiration acts as an indirect measure of labile soil organic matter reserves and the metabolic activity of the soil microbial community, by measuring the carbon dioxide released from the soil over a four-day period. Respiration levels in individual plots and alleyways (n = 32 plots + 4 alleyways) ranged from 0.5-0.9 mg CO_2 g^{-1} dry weight soil. Soil respiration was affected by the cropping system and crop rotation entry point interaction ($P = 0.003$) (Table 3). In entry point A, the RT and HF systems had greater respiration than the LF and EWM systems. In entry point B, the LF soils respired more than those in the EWM system.

Alleyway means were different (P < 0.05) from cropping system, entry point, or their interaction means for soil aggregate stability, respiration, organic matter, phosphorus, and potassium (Table 3). The alleyway had greater soil aggregate stability than the HF and EWM systems in entry point A, and the HF and LF systems in entry point B. The alleyway had greater respiration than the LF system in entry point A, and greater soil organic matter than the HF system in entry point B. The alleyway also had greater phosphorus than the LF and EWM systems in entry point A, and greater potassium than the LF system.

3.2. Soil invertebrate abundance and community structure

3.2.1. Date 1: 34 days after planting

Few differences in soil invertebrate abundances were observed at the Date 1 invertebrate sampling (Table 4). Soil invertebrate community structure at sampling Date 1 was not affected by the cropping system, crop rotation entry point, or their interaction.

Some of the most abundant taxa observed in the Date 1 invertebrate sampling include the fungivorous collembolan family Onychuridae, fungivorous, bacterivorous, and predatory mites in the families Scutacaridae, Histiostomatidae, and Rhodacaridae, as well as saprophytic/microbivorous oligochaetes in the family Enchytraeidae (see Appendix A, Table A1).

The abundance of phoretic immature astigmatid mites (hypopi) varied by cropping system (Table 4). The EWM system had greater abundances of hypopi than the other three cropping systems. However, phoretic hypopi were also indicator species for the alleyways (Table 5). The astigmatid mite family Histiostomatidae varied between the crop rotation entry points, with entry point B having a greater abundance than entry point A (Table 4). Carabid beetle larvae had cropping system and crop rotation entry point interactions, with differences between systems observed only in entry point B (Table 4). Surprisingly, more carabid beetle larvae were observed in the LF and EWM systems than in the HF and RT systems.

The collembolan family Onychiuridae was more abundant in the alleyway than in the LF system in entry point A (Table 4) and was also an indicator species for the alleyway (Table 5). Entry point A had greater Isotomidae abundance than the alleyways (Table 4). Rhodacaridae, a family of predatory mites in the order Mesostigmata, was an indicator taxon for the HF system at sampling Date 1 (Table 5). The mite families Acaridae and Tectocepheidae were indicator species for the alleyway at Date 1 (Table 5).

3.2.2. Date 2: 70 days after planting

The overall abundance of the invertebrates collected at the Date 2 sampling was greater than at the Date 1 sampling (see Appendix A, Tables A1 and A2). Some of the most abundant invertebrate taxa observed at Date 2 include the collembolan families Onychiuridae and Isotomidae, fungivorous mites in the families Scutacaridae and Acaridae, predatory mites in the family Rhodacaridae, as well as nonfeeding phoretic hypopi (see Appendix A, Table A2).

Total invertebrate abundance was affected by the cropping system and crop rotation entry point interaction (Table 4). Within entry point A, the RT system had more invertebrates than the LF system. In contrast, within entry point B, the EWM system had more invertebrates than the HF system.

The soil invertebrate community structure at sampling Date 2 was impacted by the cropping system ($P = 0.007$). The differences observed between the soil invertebrate communities in each of the cropping systems and the alleyway are illustrated using NMDS (Fig. 2). The EWM system invertebrate community was different from the invertebrate community observed in the RT system. The alleyway had a similar invertebrate community to the RT system, but was different from the EWM system.

The EWM system had more phoretic hypopi of astigmatid mites than the HF and RT systems (Table 4), and phoretic hypopi were also an indicator taxon for the EWM system (Table 5). Astigmatid mites in the family Acaridae were also influenced by cropping system; however, like total invertebrate abundance, their response varied by crop rotation entry point. Specifically, there were more Acaridae in the RT system than the LF system entry point A; however, in entry point B, the EWM system had more Acaridae than the HF and RT systems.

Abundance of mites in the family Histiostomatidae was greater in the alleyways than in the EWM and RT systems in entry point B (Table 4). The alleyway had fewer mites in the family Microdispidae than the RT system in entry point A (Table 4). The alleyway had higher numbers of mites in the family Scutacaridae than the EWM system in entry point B (Table 4). Although, Scutacaridae were an indicator taxon for the RT system at sampling Date 2 (Table 5).

Other microarthropods from across diverse taxonomic and functional groups (Onychiuridae, Isotomidae, Rhodacaridae, and immature carabids) were indicators for the alleyway (Table 5).

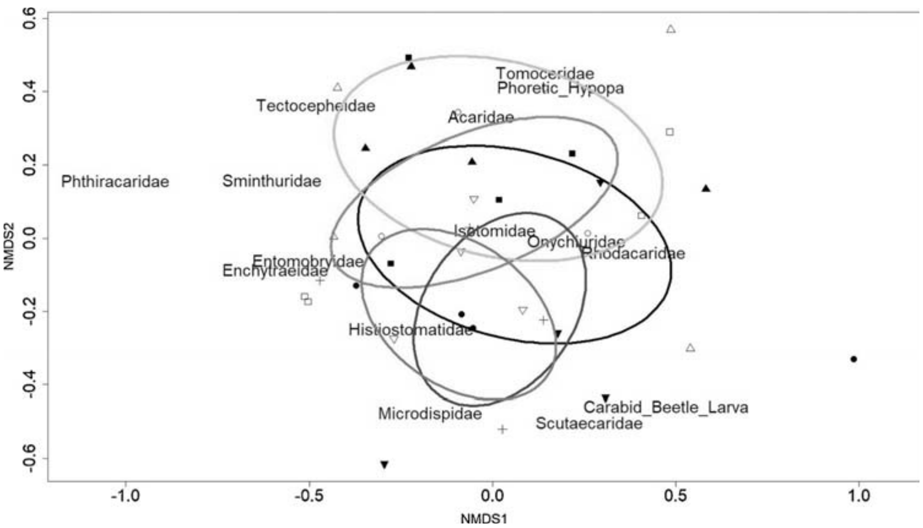

Fig. 2. Nonmetric multidimensional scaling (NMDS) ordination of the invertebrate communities at sampling Date 2 (3 dimension solution, stress = 0.165). Points represent plots (HF = circle, LF = square, EWM = up triangle, RT = down triangle, Alleyway = plus sign; Entry point A = open points, Entry point B = closed points), and ellipses show the 95% confidence intervals (HF = black, LF = red, EWM = green, RT = blue, Alleyway = purple). Cropping systems: High Fertility (HF), Low Fertility (LF), Enhanced Weed Management (EWM), and Reduced Tillage (RT).

3.3. Aboveground plant biomass

3.3.1. Weed biomass and community structure

Weed biomass in individual plots and alleyways (n = 32 plots + 3 alleyways) ranged from 7.63 g m^{-2} to 55.5 g m^{-2} and varied by crop rotation entry point (P = 0.015) (Table 6). Entry point B had an average of 40.5% more weed biomass than entry point A. Weed community structure varied by the cropping system and crop rotation entry point interaction (P = 0.002). The differences observed between the weed communities in each cropping systems by entry point and the alleyway are illustrated using NMDS (Fig. 3). Entry point A and entry point B had very different weed communities when comparing cropping systems. Within entry point A, weed community structure in the HF system was different from the weed community structure in the RT system. *Sonchus arvensis* L. (perennial sowthistle) was an indicator species for the HF system (Table 7). In contrast, *Setaria pumila* (Poir.) Roemer & J.A. Schultes (yellow foxtail), *Erigeron annuus* (L.) Pers. (annual fleabane), *Poa annua* L. (annual bluegrass), and *Pisum sativum* L. (winter pea) were all indicator species for the RT system (Table 7).Within entry point B, weed community structure in the LF system was different from the weed community structure in the RT system. *Calystegia sepium* (L.) R. Br. (hedge bindweed) and *Panicum*

Table 6

Significance levels from the ANOVAs performed on the aboveground plant biomass with means (P < 0.05, bolded). Means with the same letters are not significantly different (Fisher's LSD, P > 0.05). Upper case and lower case letters indicate that separate mean comparisons were conducted. Means that are significantly different from the alleyway mean for each column are marked with an asterisk.

	Total weed biomass g/m^2		Annual weed biomass g/m^2		Perennial weed biomass g/m^2		Weed species richness species/m^2		Sorghum sudangrass biomass g/m^2	
P-Value										
System	0.174		0.127		0.174		0.067		**0.053**	
Entry Point	**0.015**		**8.2E-05**		**0.001**		0.648		**2.4E-05**	
System x Entry Point	0.232		0.077		0.254		**0.024**		0.120	
System										
High Fertility	18.95		12.61		4.02		13.00		110.00*	**AB**
Low Fertility	18.92		12.78		5.57		12.63		97.86*	**B**
Enhanced Weed Management	14.54		10.62		2.79		11.88*		123.67*	**AB**
Reduced Tillage	22.11		17.36		2.81		14.63		129.73*	**A**
Entry Point										
A	15.55	**b**	9.33*	**b**	5.36	**a**	13.16		100.44*	**b**
B	21.84	**a**	18.47*	**a**	2.47	**b**	12.91		130.72*	**a**
Interaction										
Entry Point A										
High Fertility	12.67		6.49*		4.89		11.63*	**B**	98.81*	
Low Fertility	18.24		11.17		6.80*		13.13	**AB**	92.32*	
Enhanced Weed Management	12.85*		7.79*		4.57		12.75	**AB**	96.55*	
Reduced Tillage	19.70		13.43		5.44		15.13	**A**	115.58*	
Entry Point B										
High Fertility	28.34*		24.50*		3.30		14.38	**a**	122.47*	
Low Fertility	19.64		14.63		4.55		12.13	**ab**	103.74*	
Enhanced Weed Management	16.47		14.47		1.71		11.00*	**b**	157.82*	
Reduced Tillage	24.82*		22.45*		1.45		14.13	**ab**	145.61*	
Alleyway Means	18.2		14.35		2.95		15.5		205.5	

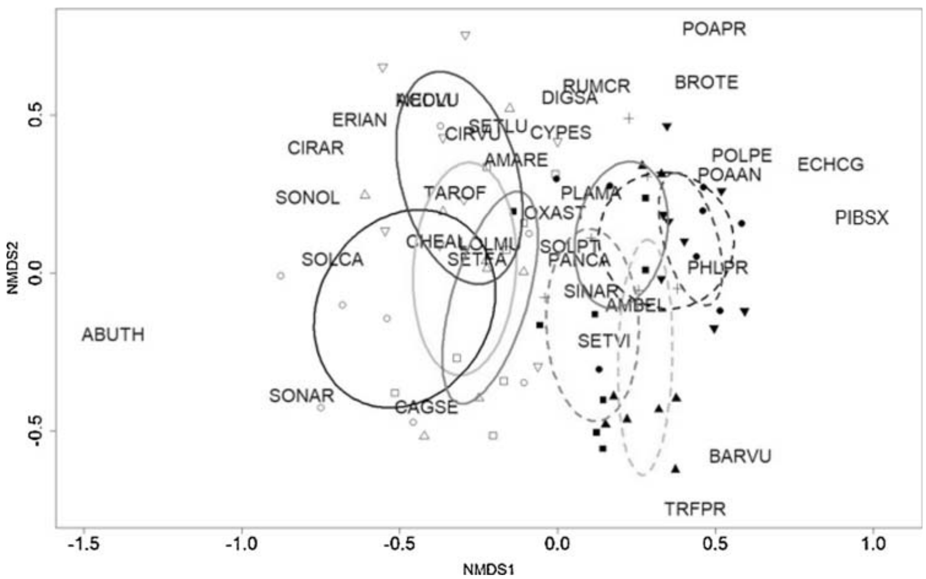

Fig. 3. Nonmetric multidimensional scaling (NMDS) ordination of the aboveground weed community (4 dimension solution, stress = 0.1187). Points represent plots (HF = circle, LF = square, EWM = up triangle, RT = down triangle, Alleyway = plus sign; Entry point A = open points, Entry point B = closed points), and ellipses show the 95% confidence intervals (HF = black, LF = red, EWM = green, RT = blue, Alleyway = purple) (Entry point A = closed ellipses, Entry point B = dashed ellipses). Weed species are labeled using EPPO codes. Cropping systems: High Fertility (HF), Low Fertility (LF), Enhanced Weed Management (EWM), and Reduced Tillage (RT).

capillare L. (witchgrass) were indicator species for the LF system (Table 7). The alleyway produced more weed biomass than the EWM system in entry point A, but less than the HF and RT within entry point B (Table 6).

Weed species richness also had a significant cropping system and crop rotation entry point interaction ($P = 0.024$) (Table 6). Within entry point A, the RT system had greater weed species richness than the HF system. However, within entry point B, the EWM system had greater weed species richness than the HF system. The weed community in the alleyway was more similar with the community in entry point B compared to entry point A (Fig. 3). *Chenopodium album* L. (common lambsquarter), *Plantago major* L. (broadleaf plantain), *Taraxacum officinale* G.H. Weber ex Wiggers (dandelion), *Amaranthus retroflexus* L. (redroot pigweed) were indicator species in the alleyways (Table 7).

3.3.2. Sorghum sudangrass biomass

Sorghum sudangrass biomass in individual plots and alleyways (n = 32 plots + 3 alleyways) ranged from 60 g m^{-2} to 255 g m^{-2}. Sorghum sudangrass biomass was affected by the crop rotation entry point ($P < 0.0001$) and by the cropping system ($P = 0.053$) (Table 6). Entry point B had more sorghum sudangrass biomass than entry point A. The RT system produced an average of 32.6% more sorghum sudangrass biomass than the LF system. The alleyway produced more sorghum sudangrass biomass than every cropping system and crop rotation entry point interaction (Table 6). On average, the alleyway produced 86.8% more biomass than the HF system, 109.9% more biomass than the LF system, 66.2% more biomass than the EWM system, and 58.4% more biomass than the RT system.

3.4. Agroecosystem relationship modeling

Piecewise structural equation modeling was used to better understand the interrelationships between soil health indicators, soil invertebrates, and aboveground biomass. Based on the calculated Fisher's C statistic and the p-value for our SEM ($C = 1.309$, $P = 0.52$), our model fit the relationships observed in the uniformity trial datasets (Fig. 4). The AIC (Akaike's information criterion) for this model is 75.3 and the BIC (Bayesian information criterion) is 132.9, which were lower than for other competing models.

FaunaF1 was composed solely of oribatid mites (immature astigmatid hypopi, Acaridae, Tectocepheidae). While related taxonomically, the taxa comprising this group differ considerable in ecology and life history. Despite these ecological differences, collectively, the oribatids comprising FaunaF1 correlated positively with soil

Table 7
Indicator species analysis results showing the weed species observed in the aboveground biomass that were associated with a cropping system ($P < 0.05$).

Weed species common name	EPPO code	Cropping system	Indicator value	Mean	Standard deviation	P-value
Common lambsquarter	CHEAL	Alleyway	42.7	24.3	8.61	**0.036**
Yellow foxtail	SETLU	Reduced Tillage	38.1	27.4	5.24	**0.042**
Broadleaf plantain	PLAMA	Alleyway	39.2	27	4.38	**0.016**
Dandelion	TAROF	Alleyway	62.7	21.3	7.19	**0.001**
Perennial sowthistle	SONAR	High Fertility	60.5	24.4	7.05	**0.001**
Hedge bindweed	CAGSE	Low Fertility	46.4	21.7	4.97	**0.001**
Redroot pigweed	AMARE	Alleyway	53.2	17.7	7.96	**0.003**
Annual fleabane	ERIAN	Reduced Tillage	31.2	13.7	6.51	**0.032**
Witchgrass	PANCA	Low Fertility	46.1	28.2	5.93	**0.014**
Annual bluegrass	POAAN	Reduced Tillage	28.8	14.3	5.79	**0.027**
Winter pea	PIBSX	Reduced Tillage	31.2	9	5.17	**0.004**

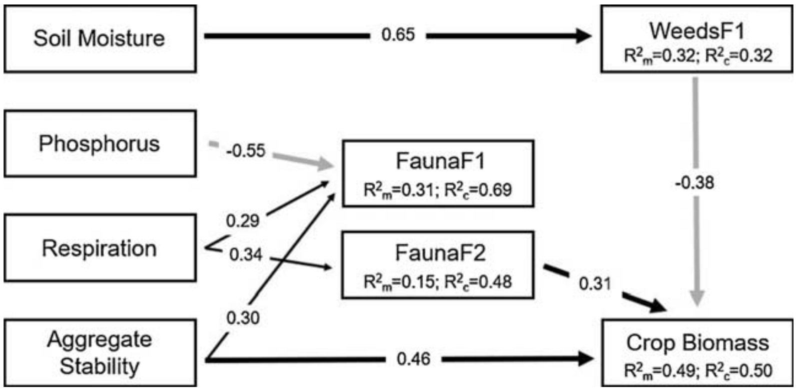

Fig. 4. Piecewise structural equation model (SEM) showing how soil health indicators, soil invertebrate groups, and weed biomass group affect crop biomass (sorghum sudangrass biomass). FaunaF1 is the group factor comprised of phoretic hypopi, Acaridae, and Tectocepheidae. FaunaF2 is the grouped factor comprised of Onychiuridae, Isotomidae, and Rhodacaridae. WeedsF1 is the grouped factor comprised of yellow foxtail, giant foxtail, and yellow nutsedge. Black arrows represent positive relationships, and grey arrows represent negative relationships. Standardized path coefficients are shown for significant relationships. Marginal (R^2_m) and conditional (R^2_c) coefficients of determination are shown for each component model, which describes the proportion of response variance associated with the fixed effects (marginal) and the fixed effects with random effects included (conditional).

aggregate stability and respiration. Contrary to our hypothesized SEM (Fig. 1), FaunaF1 was negatively correlated with phosphorus. FaunaF1 was not correlated to soil moisture or WeedsF1. Soil aggregate stability, respiration and phosphorus explained a moderate proportion of model variance ($R^2_m = 0.31$). Inclusion of the cropping system nested in the block improved the model fit significantly ($R^2_c = 0.69$).

The invertebrates comprising FaunaF2, represented a mix of collembolans and predatory mites (Onychiuridae, Isotomidae, and Rhodacaridae), and were positively correlated with soil respiration. Respiration explained a small proportion of the model variance ($R^2_m = 15\%$). Inclusion of the cropping system nested in the block improved the model fit greatly ($R^2_c = 48\%$).

WeedsF1, the grouped factor comprised of *Setaria pumila* (Poir.) Roemer & J.A. Schultes (yellow foxtail), *Setaria faberi* Herrm. (giant foxtail), and *Cyperus esculentus* L. (yellow nutsedge), was correlated with soil moisture. WeedsF1 was not correlated with the other soil health indicators included in the model. A moderate proportion of the model variance ($R^2_m = 32\%$) was explained by the included predictor variables.

Sorghum sudangrass biomass was positively correlated with soil aggregate stability. This finding is affirmed by the aggregate stability and sorghum sudangrass biomass ANOVA results (Table 3; Table 6), showing the RT system had greater soil aggregate stability as well as greater sorghum sudangrass biomass production. Sorghum sudangrass biomass was also positively correlated with FaunaF2. Sorghum sudangrass biomass was indirectly correlated to soil respiration through FaunaF2. As hypothesized in our SEM model (Fig. 1), WeedsF1 was negatively correlated with sorghum sudangrass biomass. Sorghum sudangrass was also indirectly correlated with soil moisture. A fairly large proportion of the model variance ($R^2_m = 49\%$) was explained by the included predictor variables.

4. Discussion

4.1. Legacy effects of crop management practices

4.1.1. Soil disturbance legacy effects

Soil disturbance directly impacts biological communities in soils, and is capable of having observable legacy effects on various organisms including soil invertebrates (Crotty et al., 2016; Kladivko, 2001). The moldboard plowing prior to sampling Date 1 likely decreased the abundance in invertebrates, however the time between the two sampling dates may have allowed the invertebrate communities to recover from the tillage event before sampling Date 2 (Nkem et al., 2002). The soil invertebrate community structure at sampling Date 2 was impacted by the cropping system, which was largely driven by the differences in soil disturbance histories between the Enhanced Weed Management and Reduced Tillage systems. The Enhanced Weed Management system was characterized by an increase in astigmatid mite abundance, whereas the Reduced Tillage system was characterized by an increase in the abundance of multiple families of Collembola. The Enhanced Weed Management system had greater abundances of hypopi at both Date 1 and Date 2 sampling events, and the hypopi were also an indicator taxon for this system at sampling Date 2. The hypopi of astigmatid mites are a non-feeding, specialized instar that is a heavily protected dispersal stage for these mites, which enables them to tolerate and recover from disturbance well (Evans et al., 2013). Astigmatid mite populations increase in environments where soil disturbances are more frequent since they are more disturbance tolerant (Hülsmann and Wolters, 1998; Reeleder et al., 2006; Wardle, 1995). Tillage often reduces the abundance of carabid beetles in agricultural settings (Kosewska et al., 2014), so it was surprising to see that in entry point B the Enhanced Weed Management and Low Fertility systems had greater abundances of carabid beetle larvae at sampling Date 1. However, carabid beetle species have been shown to respond to tillage regimes differently, and it has been proposed that conventional tillage may create habitats that are more preferable to xerophilic spring breeding carabid beetles (Hatten et al., 2007).

The reduced soil disturbance in the Reduced Tillage system likely improved the soil structure and water holding capacity and infiltration in this cropping system, as evident by the greater soil aggregate stability and soil surface moisture (Gallardo-Carrera et al., 2007). Most of the precipitation that occurred during the uniformity trial happened shortly after the sorghum sudangrass was planted in two large rainfall events: (1) one day after planting (46.5 mm) and (2) 12 days after planting (80.5 mm). Heavy rains and consistently wet weather during critical growth periods in the uniformity trial appear to have had a strong influence on the aboveground plant biomass. The improved soil aggregate stability in this system may have also helped to mitigate the negative effects of the very wet growing conditions experienced during the growing season, since the Reduced Tillage system produced an average of 32.6% more sorghum sudangrass biomass than the Low Fertility system. Previous research has shown that reduced tillage systems and high soil aggregate stability do not necessarily lead to higher crop yields (Paul et al., 2013; Reinhart and Vermeire, 2016); however, our uniformity trial was a unique assessment of legacy effects and took place during a season with very high precipitation. Additionally, Reduced Tillage soils had more phosphorus than the Low Fertility system, which likely contributed to the greater sorghum sudangrass biomass production. Our SEM highlighted the importance of legacies of soil aggregate stability, soil surface moisture, and soil phosphorus in determining agroecosystem functioning and sorghum sudangrass biomass production across the different cropping systems during the uniformity trial.

In contrast to the other cropping systems, weeds in the Reduced Tillage system were likely subjected to greater competition from sorghum sudangrass, which may have influenced the weed community. However, it is more likely that the tillage history of this cropping system contributed to a more distinct weed community, which was highlighted by the greater number of indicator taxa in this system. *Setaria pumila* (Poir.) Roemer & J.A. Schultes (yellow foxtail), *Erigeron annuus* (L.) Pers. (annual fleabane), *Poa annua* L. (annual bluegrass), and *Pisum sativum* L. (winter pea) were all indicator species for the Reduced Tillage system (Table 7). Winter pea was the previous crop planted in this system, which explain why it was an indicator species in this system the following season. The other weeds identified as indicator species are all annuals and were likely prompted to germinate due to the moldboard plowing at the beginning of the uniformity trial, a practice that had rarely occurred in the Reduced Tillage system since 2005 (Caldwell et al., 2014).

4.1.2. Resource input legacy effects

Resource inputs, including fertilizers (compost and chemical organic fertilizers) and plant residues (green manures), are important for long- and short-term nutrient management in agroecosystems. The only observable long-term legacy effect of the different fertilizer regimes was the difference in the amount of phosphorus that had accumulated in the soil. The High Fertility system likely had greater soil phosphorus levels because of the greater cumulative nutrient inputs it received compared to the other cropping systems (Caldwell et al., 2014). The Reduced Tillage also had comparable phosphorus levels to the High Fertility system, however the accumulation of phosphorus in this system is likely due to the lower crop yields that resulted in less nutrient removal in the Reduced Tillage system throughout the experiment (Caldwell et al., 2014). The RT system also received additional poultry manure in 2007 and 2008 when the legume cover crop was inadequate (Caldwell et al., 2014), which may have also contributed to the relatively high phosphorus levels that were observed in this system. The SEM created from the uniformity trial dataset suggests that the long-term accrual of phosphorus in the soil is an important driver of future crop productivity.

Our results suggest that it is important to consider both the long- and short-term input legacies. The High Fertility system had greater cover crop biomass prior to the uniformity trial, which may have been caused by the greater soil phosphorus levels in this system. Our findings indicate that such resource input legacies are also important for soil invertebrates. The predatory Rhodacaridae may have preferred the High Fertility system at sampling Date 1 due to the greater previous cover crop biomass, since it has been shown that predatory invertebrates do well in environments with more complex vegetation (Finke and Denno, 2002). Thus, biomass, rather than the chemical or nutritional quality, of the resource input seemed to be the driver of the rhodacarid abundances.

The astigmatid mite family Histiostomatidae had a greater abundance in entry point B, which is also likely due to the type of plant biomass that was produced in the different crop rotation entry points in the previous growing season. Phoretic immature histiostomatids may have attached to mobile insects that preferred the red clover and winter pea (Reduced Tillage) planted in entry point B, therefore moving more of the hypopi into entry point B that would later mature into the Histiostomatidae observed at the Date 1 invertebrate sampling. This proposed mechanism is not established in the literature and is an important area in soil mite ecology that has yet to be studied, though there is evidence that surface dwelling arthropods exhibit vegetation preferences (Eyre et al., 2016). In contrast to the preferences exhibited by rhodacarids, the responses of the Histiostomatidae suggests that for some taxa the nutritional quality, or some other taxon-specific plant trait, is more important that total biomass production.

The crop rotation entry point effects are largely dominated by the effects caused by the previous crops planted in each entry point prior to the uniformity trial. The effects of the previous crop in each entry point, as well as the management of those different crops, highlights the short-term effects in cropping systems. Entry point B had an average of 24.7% more phosphorus, 40.5% more weed biomass, and 30.1% more sorghum sudangrass biomass than entry point A. The greater soil phosphorus levels and greater plant biomass production in the uniformity trial is likely due to the poultry manure application prior to the last cash crop in entry point B (spelt), which did not occur in entry point A (corn), as well as the greater nitrogen levels in entry point B from the legume cover crops present in that entry point before the uniformity trial. Additionally, the different cover crops in the two entry points prior to the uniformity trial, annual ryegrass and red clover, likely suppressed the weeds differently, leading to differences in weed seed production prior to this uniformity trial.

Resource inputs appeared to have moderated the effects of soil disturbance in the cases of soil organic matter, respiration, and total soil invertebrates at sampling Date 2. Organic amendments are important for increasing soil organic matter, therefore we predicted that the soil organic matter content would have been greater in the High Fertility system due to the greater levels of organic amendments applied in the system. However, we found that in entry point B the High Fertility system had the lowest soil organic matter. Nutrient priming may have played a role in this effect due to the high-nutrient poultry litter additions incorporated in this system compared to the other three cropping systems (Kallenbach and Grandy, 2011). The High Fertility system also had more intensive tillage than the Reduced Tillage system, which may also have negated the benefits of organic matter additions. The reduced soil aggregate stability in the High Fertility system would have resulted in less protection of soil organic matter and a greater vulnerability to decomposition. Soil organic matter is often bound within soil aggregates where it can be protected from microbial decomposition; therefore, the relationship between soil organic matter and aggregate stability is usually positively correlated (Abiven et al., 2009; Belmonte et al., 2018). Within entry point B, the Reduced Tillage system had greater soil organic matter than the High Fertility system, which was likely due to the reduced amount of tillage and more stable soil aggregates in the system (Chivenge et al., 2007).

Respiration is indirectly linked to management practices through the management effects on soil organic matter, aggregate stability, and soil moisture. The differences in these soil characteristics between the systems in entry point A can be attributed to differences in nutrient inputs and tillage practices throughout the experiment (Fiedler et al., 2015). The differences between the systems in entry point B are similar to the differences in entry point A, except for the Low Fertility system. The red clover cover crop grown before the uniformity trial may have had a greater effect on the microbial community in the Low Fertility system in entry point B since the higher quality inputs would have stimulated microbial growth and activity in this nutrient depleted system (Brackin et al., 2014).

The general preference of invertebrates for the Reduced Tillage system in entry point A likely reflects a community-wide positive response of soil invertebrates to the reduced number of cultivation events, particularly moldboard plowing (Bedano et al., 2006; Wardle, 1995; Winter et al., 1990). However, the preference for the Enhanced Weed Management system in entry point B appears contradictory, as this system experienced more primary and shallow tillage events than any other cropping system. It is possible that the preference for Enhanced Weed Management observed under entry point B reflects the response of individual invertebrate taxa, particularly disturbance-tolerant astigmatid mites, rather than a whole-community response (Reeleder et al., 2006). Results from entry point A align with previous studies showing that tillage can have negative legacy effects on soil microarthropod abundances (Adl et al., 2006). However, the discrepancies we observed between entry point A and entry point B suggest that the relative importance of soil disturbance legacy effects varies based on resource input (cover crop residue) legacy, specifically related to the effect of the crop residue on soil organic carbon. This finding is particularly insightful for astigmatid mites in the family Acaridae, since they followed a similar pattern to the total abundances at Date 2. This suggests that the utility of Acaridae as disturbance indicators is highly context dependent. Acaridae, while being relatively disturbance tolerant, are actively feeding fungivores which may be why their response to disturbance is often dependent on resource legacy effects (Evans et al., 2013).

Weed community structure also varied by the cropping system and crop rotation entry point interaction. This result is supported by findings that weed communities are affected by tillage regimes and crop type (Armengot et al., 2016; Jernigan et al., 2017). Entry point A and entry point B had very different weed communities when comparing cropping systems, suggesting that the previous crop in a rotation can profoundly influence weed emergence and growth. Weed species richness also had an interesting interaction effect that mimicked the pattern of total invertebrates and Acaridae at Date 2, which may suggest that biodiversity aboveground may relate to the abundances of soil invertebrates belowground.

4.1.3. Field alleyway legacy effects

The field alleyways allow for a unique comparison of the legacy effects of soil disturbance and resource inputs in an agricultural setting. Throughout the long-term experiment, the soil in the field alleyways was not disturbed by tillage from its initiation until the uniformity trial. The alleyways had continuous mixed vegetation that provided a constant input of root exudes and fine root turnover. Plant roots are more effective at promoting soil aggregation than adding external nutrient sources, therefore greater root carbon inputs tend to have a greater impact on soil organic carbon accrual (Baumert et al., 2018). Root inputs from the continuous vegetation within alleyways may also explain why these systems had overall better soil health compared to the cropping systems, specifically greater soil aggregate stability, respiration, organic matter, phosphorus, and potassium. The improved soil health in the alleyway, especially the greater soil aggregate stability, likely contributed to the alleyway producing the greatest sorghum sudangrass biomass.

In addition to improved soil health, the alleyways had the greatest number of soil invertebrate indicator taxa compared to the cropping systems at both sampling dates. At sampling Date 1, Tectocepheidae, a family of saprotrophic mites with the order Oribatida, may have preferred the soil physical structure in the alleyways, which had relatively high soil aggregate stability compared to most of the cropping systems (Dhooria, 2016; Fujita and Fujiyama, 2001).

While astigmatid abundances often spike following disturbance, some taxa appear to prefer more stable soil habitats like the alleyways which may be the case for the Acaridae. At sampling Date 1 phoretic hypopi were an indicator species for the alleyways; however, the abundance of the hypopi were comparable in the Enhanced Weed Management system, which suggests that astigmatid mite responses to management practices like tillage are more nuanced than previous thought. At sampling Date 2, the Onychiuridae, Isotomidae, Rhodacaridae, and immature carabids that were indicator species for the alleyway are taxonomically diverse. Ecologically, these taxa function as detritivores, microbivores, and predators, and thus potentially contribute to multiple soil ecosystem services including biological control, crop residue decay, and nutrient cycling.

Shortly after tillage, at the Date 1 sampling for soil invertebrates, the collembolan family Onychiuridae was more abundant in the alleyway which may be attributed to collembolans' preference for soils that are disturbed less frequently (Dittmer and Schrader, 2000). However, crop rotation entry point A had greater Isotomidae abundance than the alleyways. The collembolan family Isotomidae impacts organic matter decomposition processes in the soil ecosystem (Andren and Schnurer, 1985), and was therefore likely more impacted by the residue decomposition legacy effect (Crotty et al., 2016).

At the Date 2 sampling for soil invertebrates, there were greater abundances of Histiostomatidae, Scutacaridae, and Microdispidae in the alleyways. Each of these mite families have been found to be phoretic on soil-nesting insects including ants and bees (Khaustov, 2015; Moser and Blomquist, 2011; Navabi et al., 2018; Rahiminejad et al., 2015; Sobhi et al., 2017). These soil-nesting insects likely preferred the areas with less soil disturbance, and most likely carried these phoretic mites into these areas as they moved throughout the landscape. Additionally, scutacarids are likely fungivorous and the reduced soil disturbance in the alleyway and the Reduced Tillage system may have supported greater fungal biomass than the other cropping systems (Cao et al., 2011b)

Alleyways are known to be reservoirs for biodiversity in agricultural systems. These reservoirs are beneficial for natural predator populations, however it has remained unclear whether undisturbed habitat patches serve the same purpose (ecological reservoirs) for soil biota as they do for more mobile invertebrates (Fukuda et al., 2011; Todd et al., 2018). Our results suggest that field alleyways and other field borders may also be important biodiversity reservoirs for certain soil invertebrates.

4.2. Agroecosystem relationships across cropping systems

Soil respiration and aggregate stability positively impacted the oribatid mites comprising FaunaF1. Greater microbial respiration measurements are indicative of a more active microbial community with potentially greater biomass (Anderson and Domsch, 1978). This relationship supports previous findings that many soil fauna are sensitive to changes in soil microbial community traits (Gan et al., 2014). The invertebrates composing FaunaF1 may also be sensitive to the size of the labile carbon pool or soil organic carbon composition, which is altered by microbial degradation (Soong et al., 2018). Soil aggregate stability is indicative of a less disturbed soil environment, which likely also benefited some of the invertebrate taxa composing FaunaF1. The responses to disturbance of the specific taxa composing FaunaF1 are likely highly context dependent in regard to soil organic matter and soil organic carbon (Tabaglio et al., 2009). Interestingly, we found that FaunaF1 was negatively correlated with phosphorus, which partially supports previous research showing that high phosphorus levels reduce the abundance of oribatid mites in grain cropping systems, possibly due to the suppression of fungal growth, thus decreasing food availability for some fungivorous microarthropods (Cao et al., 2011b).

As with FaunaF1, FaunaF2 was also positively correlated with soil respiration. Collembola have been shown to stimulate microbial activity and nutrient cycling as they graze on microbial biomass (Caravaca and Ruess, 2014). In contrast, the linkages between rhodacarids and soil microbial activity (e.g. respiration) are less intuitive. Rhodacarids are active soil mesopredators, and may stimulate microbial activity indirectly through the regulation of their microbivorous prey, which suggests that there are cascading trophic effects in this system. These two possible explanations are contradictory, however the consequences of specific trophic interactions in the soil are not well established (Kaspari and Yanoviak, 2009). In addition to serving as an indicator of soil microbial activity, soil respiration also partly reflects the size of the resource base for the microbivorous taxa included in FaunaF2 (Anderson and Domsch, 1978).

WeedsF1 was positively impacted by soil moisture, which may be attributed to the poor productivity of sorghum sudangrass in wet areas of the field, which allowed for the weeds to produce more biomass in those areas. Yellow nutsedge is also known for its growth in wet areas (Wilen et al., 1996). Sorghum sudangrass biomass was also positively correlated with FaunaF2. Collembolans, including onychiurids and isotomids, are well known to have positive impacts on nutrient cycling (Filser, 2002), which links them indirectly to crop yield. The positive relationship observed between FaunaF2 and sorghum sudangrass biomass may also be affected by the role that the predatory mites in the family Rhodacaridae play in biological control of soil pests including nematodes and thrips (Castilho et al., 2009). FaunaF2 also mediated the relationship between soil respiration and sorghum sudangrass biomass. Previous research has shown inconsistent direct correlations between microbial respiration and crop yields (Chirinda et al., 2010; Hungria et al., 2009). This result suggests that soil invertebrates, specifically the presence of microarthropods that graze heavily on microbial biomass, play an important role in mediating the effects that microbial communities have on crop production. This interaction probably expands to higher trophic levels in soil food webs, since predatory mites may have also contributed to linking soil microbial communities to crop productivity. These results support the microbial loop model, which postulates the role of multi-trophic interactions in supplying nitrogen and phosphorus to crops (Clarholm, 1985). The negative relationship between WeedsF1 and sorghum sudangrass biomass was expected, as weed-crop competition is known to reduce crop yield (Zimdahl, 2004). Sorghum sudangrass was also indirectly correlated with soil moisture, which highlights the important influences that abiotic factors like precipitation can have on agroecosystem relationships.

4.3. Conclusions

Results from this uniformity trial highlight the effects of different soil and crop management practices on soil health indicators, weed abundance, and crop productivity, and the relationships between these different metrics of agroecosystem functioning. Within our SEM model, crop productivity was directly correlated with aggregate stability and an unexpected soil invertebrate group, while also being indirectly correlated with microbial respiration through soil invertebrates. This research suggests that direct biological measurements can be a valuable component of agroecosystem assessments and shows the importance of accounting for multiple trophic interactions when attempting to quantify agroecosystem functioning. Soil biota can be important drivers of plant health, but our results indicate their contributions are much more nuanced than can be captured simply by measuring overall abundance of coarse taxonomic groups. Some soil health tests are now incorporating direct counts of bacteria, fungi, protozoa, and nematodes, however the number of studies showing clear linkages between soil fauna and crop yield is very limited. Additional research on direct biological measurements is needed in order to confirm their utility and meaningfully integrate such analyses into assessments of overall agroecosystem functioning. It is also important to note that the results from this research should be interpreted with some caution given that the uniformity trial was only conducted in one growing season. Interestingly, the legacy effects of the cropping systems differed in terms of chemical, physical, and biological soil health indicators, which highlights the impact of different management strategies used within organic cropping systems. Overall our findings suggest that crop and soil management practices that improve soil health and support taxonomically diverse, multi-trophic soil communities can enhance crop productivity, if weeds are adequately suppressed.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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Appendix A

Table A1
Significance levels from the ANOVAs performed on the soil invertebrates from the Date 1 sampling with means ($P < 0.05$, bolded). Means with the same letters are not significantly different (Fisher's LSD, $P > 0.05$). Upper case and lower case letters indicate that separate mean comparisons were conducted. Means that are significantly different from the alleyway mean for each invertebrate group are marked with an asterisk. Soil invertebrate units are # invertebrates Kg^{-1} soil.

	Total Invertebrates	Onychiuridae	Isotomidae	Entomobryidae	Tomoceridae	Sminthuridae	Rhodacaridae	Histiostomatidae		Microdispidae
P-Value										
System	0.284	0.384	0.463				0.097	0.230		0.765
Entry Point	0.172	0.664	0.286				0.915	**0.043**		0.376
System x Entry Point	0.148	0.856	0.132				0.441	0.082		0.667
System										
High Fertility	56.1	7.53	0.45	0	0	0.68	16.32	2.73		1.90
Low Fertility	37.7	1.51*	< 0.0001	0	0	0	2.81	3.64		1.43
Enhanced Weed Management	51.9	2.30*	0.88	0	0	0	4.00	0.15		4.02
Reduced Tillage	32.3	4.83	0.15	0	0	0	2.26	0.63		1.88
Entry Point										
A	39.3	3.22*	0.44*	0	0	0	5.45	0.64	**B**	1.56
B	48.9	4.19*	0.11	0	0	0.34	5.17	2.47	**A**	2.97
Interaction										
Entry Point A										
High Fertility	43.9	5.24	1.79	0	0	0	11.98	0.30		1.24
Low Fertility	27.7	0.91*	< 0.0001	0	0	0	2.18	2.48		0.28
Enhanced Weed Management	46.7	2.57	1.77	0	0	0	4.83	< 0.0001		3.01
Reduced Tillage	40.4	5.45	< 0.0001	0	0	0	4.86	1.19		2.64
Entry Point B										
High Fertility	69.9	10.22	< 0.0001	0	0	1.36	21.34	7.61		2.69
Low Fertility	49.2	2.27	0	0	0	0	3.53	5.03		3.48
Enhanced Weed Management	57.5	2.03	0.30	0	0	0	3.26	0.60		5.18
Reduced Tillage	25.1	4.24	0.58	0	0	0	0.63	0.26		1.25
Alleyway Means	67.6	15.92	0	0	0	0	8.32	4.35		0.30

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Table A1 (*continued*)

	Scutacaridae	Phoretic Hypopi		Phthiracaridae	Acaridae	Tectocepheidae	Diplopoda	Enchytraeidae	Carabid Beetle Larva	
P-Value										
System	0.833	**0.003**			0.628	0.605	0.999	0.937	0.621	
Entry Point	0.394	0.202			0.504	0.878	0.935	0.099	0.340	
System x Entry Point	0.491	0.644			0.265	0.066	0.271	0.752	**0.025**	
System										
High Fertility	3.95	0.68	**B**	0	1.42	0.00	0.09	3.55	0	
Low Fertility	1.88	1.49	**B**	0	0.43	0.14	0.07	2.46	0.88	
Enhanced Weed Management	4.00	9.33	**A**	0	1.97	0.55	0.07	3.23	0.40	
Reduced Tillage	2.66	0.40	**B**	0	0.30	0.08	0.08	3.86	0.31	
Entry Point										
A	3.97	1.30		0	1.24	0.19	0.07	1.99	0.30	
B	2.26	2.99		0	0.62	0.24	0.08	4.98	0.76	
Interaction										
Entry Point A										
High Fertility	6.05	0.30		0	0.31	0	< 0.0001	2.75	0	**A**
Low Fertility	4.87	0.27		0	0.61	0.56	0.27	1.15	0.27	**A**
Enhanced Weed Management	2.77	7.41		0	4.10	< 0.0001	0.28	1.09	< 0.0001	**A**
Reduced Tillage	2.69	0.58		0	1.19	0.30	0	3.48	1.23	**A**
Entry Point B										
High Fertility	2.29	1.23		0	3.35	0	0.34	4.46	0	**b**
Low Fertility	0.29	3.66		0	0.29	0	< 0.0001	4.27	1.83	**a**
Enhanced Weed Management	5.46	11.47		0	0.61	2.19	< 0.0001	6.52	1.60	**a**
Reduced Tillage	2.63	0.26		0	< 0.0001	0	0.32	4.25	< 0.0001	**b**
Alleyway Means	0.30	9.45		0	6.49	2.65	0	0.63	0.31	

Table A2
Significance levels from the ANOVAs performed on the soil invertebrates from the Date 2 sampling with means ($P < 0.05$, bolded). Means with the same letters are not significantly different (Fisher's LSD, $P > 0.05$). Upper case and lower case letters indicate that separate mean comparisons were conducted. Means that are significantly different from the alleyway mean for each invertebrate group are marked with an asterisk. Soil invertebrate units are # invertebrates Kg^{-1} soil.

	Total Invertebrates		Onychiuridae	Isotomidae	Entomobryidae	Tomoceridae	Sminthuridae	Rhodacaridae	Histiostomatidae	Microdispidae
P-Value										
System	0.355		0.186	0.183	0.694	0.683	0.565	0.898	0.838	0.330
Entry Point	0.163		0.089	0.475	0.985	0.794	0.567	0.183	0.989	0.221
System x Entry Point	**0.006**		0.696	0.161	0.694	0.318	0.556	0.163	0.592	0.845
System										
High Fertility	138.3		37.8	3.51	0.07	0.06	0.31	14.96	3.05	2.56
Low Fertility	155.0		32.6	4.02	0	0.07	0.08	13.34	5.14	2.28
Enhanced Weed Management	257.6		51.4	3.21	0.65	0.66	0	16.14	1.87*	1.45
Reduced Tillage	189.7		58.5	10.43	0.29	0.16	0	17.41	3.43	6.37
Entry Point										
A	167.2		36.8	4.17	0.30	0.15	0.08	13.36	3.25	4.14
B	198.4		52.9	5.81	0.29	0.22	0.30	17.64	3.29*	1.91
Interaction										
Entry Point A										
High Fertility	148.3	**AB**	5.24	1.79	0	0.24	1.24	12.38	1.57	3.56
Low Fertility	91.3	**B**	0.91	0	0	0.27	0	7.87	9.32	2.28
Enhanced Weed Management	211.5	**AB**	2.57	1.77	1.15	0.29	0	13.32	1.22	3.45
Reduced Tillage	238.7	**A**	5.45	0	0.31	0	0	21.60	3.26	8.32*
Entry Point B										
High Fertility	128.6	**b**	10.22	0	0.29	< 0.0001	1.20	17.78	5.03	1.72
Low Fertility	235.3	**ab**	2.27	0	0	0	1.23	20.24	2.19	2.29
Enhanced Weed Management	308.2	**a**	2.03	0.30	0.29	1.18	0	19.23	2.67*	0.30
Reduced Tillage	146.4	**ab**	4.24	0.58	0.28	0.62	0	13.68	3.60*	4.67
Alleyway Means	238.2		79.8	19.15	0	0	0.32	28.85	9.18	2.66

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Table A2 (*continued*)

	Scutacaridae	Phoretic Hypopi		Phthiracaridae	Acaridae		Tectocepheidae	Diplopoda	Enchytraeidae	Carabid Beetle Larva
P-Value										
System	0.078	**0.024**		0.740	0.330		0.309		0.670	0.786
Entry Point	0.845	0.675		0.995	0.691		0.245		0.141	0.477
System x Entry Point	0.387	0.098		0.411	**0.014**		0.119		0.507	0.502
System										
High Fertility	5.02	45.51	**B**	0.07	7.60		1.01	0	0.42	0
Low Fertility	2.37	72.24	**AB**	0.07	5.20		3.82	0	1.54	0
Enhanced Weed Management	0.67*	140.13	**A**	0.29	23.30		4.60	0	0.44	0.16
Reduced Tillage	23.43	25.08	**B**	< 0.0001	7.59		1.03	1.23	0.88	0.30
Entry Point										
A	6.00	59.60		0.13	10.89		3.42	0.61	0.33	0.07
B	5.15	81.88		0.13	9.06		1.46	0	1.37	0.45
Interaction										
Entry Point A										
High Fertility	1.77	53.10		< 0.0001	11.85	**AB**	4.04	< 0.0001	2.75	0
Low Fertility	3.03	23.53		0.30	1.64	**B**	2.60	0.27	1.15	0.27
Enhanced Weed Management	0.30	101.54		0.29	12.22	**AB**	3.07	0.28	1.09	< 0.0001
Reduced Tillage	38.28	24.00		< 0.0001	24.82	**A**	4.10	0	3.48	1.23
Entry Point B										
High Fertility	9.93	24.08		0.29	4.29	**b**	< 0.0001	0.34	4.46	0
Low Fertility	1.78	104.40		0	10.78	**ab**	5.27	< 0.0001	4.27	1.84
Enhanced Weed Management	1.20*	137.18		0.29	37.92	**a**	6.42	< 0.0001	6.52	1.60
Reduced Tillage	12.20	5.21		< 0.0001	0.28	**b**	< 0.0001	0.32	4.25	< 0.0001
Alleyway Means	12.56	44.30		0	4.30		3.89	0	2.82	3.47