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Soil fertility and crop yields in long-term organic and conventional cropping systems in Eastern Nebraska

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Abstract

Organic agriculture aims to build soil quality and provide long-term benefits to people and the environment; however, organic practices may reduce crop yields. This long-term study near Mead, NE was conducted to determine differences in soil fertility and crop yields among conventional and organic cropping systems between 1996 and 2007. The conventional system (CR) consisted of corn (*Zea mays* L.) or sorghum (*Sorghum bicolor* (L.) Moench)–soybean (*Glycine max* (L.) Merr.)–sorghum or corn–soybean, whereas the diversified conventional system (DIR) consisted of corn or sorghum–sorghum or corn–soybean–winter wheat (wheat, *Triticum aestivum* L.). The animal manure-based organic system (OAM) consisted of soybean–corn or sorghum–soybean–wheat, while the forage-based organic system (OFG) consisted of alfalfa (*Medicago sativa* L.)–alfalfa–corn or sorghum–wheat. Averaged across sampling years, soil organic matter content (OMC), P, pH, Ca, K, Mg and Zn in the top 15 cm of soil were greatest in the OAM system. However, by 2008 OMC was not different between the two organic systems despite almost two times greater carbon inputs in the OAM system. Corn, sorghum and soybean average annual yields were greatest in either of the two conventional systems (7.65, 6.36 and 2.60 $Mg\,ha^{-1}$, respectively), whereas wheat yields were greatest in the OAM system (3.07 $Mg\,ha^{-1}$). Relative to the mean of the conventional systems, corn yields were reduced by 13 and 33% in the OAM and OFG systems, respectively. Similarly, sorghum yields in the OAM and OFG systems were reduced by 16 and 27%, respectively. Soybean yields were 20% greater in the conventional systems compared with the OAM system. However, wheat yields were 10% greater in the OAM system compared with the conventional DIR system and 23% greater than yield in the OFG system. Alfalfa in the OFG system yielded an average of 7.41 $Mg\,ha^{-1}$ annually. Competitive yields of organic wheat and alfalfa along with the soil fertility benefits associated with animal manure and perennial forage suggest that aspects of the two organic systems be combined to maximize the productivity and sustainability of organic cropping systems.

Key words: long-term crop rotations, organic farming, animal manure, perennial forage, organic matter content, soil phosphorus, nutrient budgets

Introduction

Spurred on by concerns about increasing farm size, environmental pollution, reduced biodiversity across the landscape and increased consumer demand for organic products, investigators have reported on long-term studies of differences between conventional and organic cropping systems[1–6], often with contradictory results. Compared with conventional cropping systems, reduced yields were reported for most crops in organic systems[1,2,5,6], whereas some organic systems produced equal or greater yields[3]. Yield differences between the two cropping systems are often crop specific. For example, wheat yields are often comparable in organic and conventional cropping systems[5,6]. During the first four cycles of a long-term crop rotation experiment (1975–1991) in east central Nebraska, there were no significant differences in corn or soybean yields between conventional and organic systems in a four-year rotation; moreover, corn yields were consistently greater in rotation than in continuous corn[7].

Complex, diverse and extended crop rotations are an essential component of sustainable crop production[8]. Organic cropping systems rely on diverse rotations to provide pest control and increase crop nutrition through biological nitrogen fixation and recycling of nutrients[9]. Additionally, organic cropping systems often rely on organic soil amendments such as farmyard manure or compost. Both crop rotation and manure amendments have been shown to improve grain yield compared with continuous cropping systems with synthetic fertilizers[10]. Moreover, organic soil amendments have been associated with improved soil properties such as increased soil organic matter content (OMC) and water-holding capacity, lower bulk density and enhanced pH stabilization[3,11–13]. Soil organic matter is thought to drive the productivity and sustainability of organic systems as it provides a nitrogen reservoir and increases soil water-holding capacity[3,14]. Animal manure amendments also have been shown to increase soil levels of essential nutrients including Ca, Mg, K and P[15,16].

Including perennial forage such as alfalfa in rotation may improve crop yields, soil structure, OMC and nutrient cycling[17]. Alfalfa is particularly desirable due to its capacity to biologically fix atmospheric N. In a recent study, corn grain yield in an extended rotation with alfalfa and no additional N input was not different from corn supplemented with synthetic N fertilizer; the leguminous forage provided sufficient N for the subsequent corn crop. However, soil P levels decreased in the rotation with alfalfa, presumably the result of crop removal[18]. Organic systems that include forage removal (e.g., alfalfa) and limited manure or compost application may reduce available P below critical crop response values, depending on initial soil P balance, yield of removed grain and forage, and frequency and rate of manure application[19]. Over time, grain-based annual cropping systems may become N-limited, while rotations that include perennial forage and grain crops may become P-limited[19]. Therefore, a combination of legumes, forages and organic amendments such as animal manure may be required for the maintenance of soil nutrients and OMC in organic cropping systems.

In 1975, the Long-Term Crop Rotation experiment was initiated at the Agricultural Research and Development Center (ARDC) near Mead, NE to determine the effects of crop rotation and animal manure on grain yield. The first four cycles of the rotation were reported by Lesoing[7] (stage one of the long-term experiment). Redesigned in 1996, the experiment now includes a forage-based organic cropping system in the comparisons between organic and conventional cropping systems (stage two of the long-term experiment). Stage two of the experiment was designed from a 'systems-based' perspective, with the goal of understanding some of the complex differences between realistic organic and conventional cropping systems. While this experimental approach offers practical insight regarding these different cropping systems, it does limit the discovery of mechanistic 'cause and effect' relationships typical of factorial experiments[20].

Objectives of this study were to determine the effects of long-term management and cropping system on soil chemical and physical properties and how these factors contribute to grain yield. We hypothesized that continued application of semi-composted bovine manure will: (1) maintain or increase the already greater levels of soil nutrients (P, Ca, Mg, K and Zn), soil pH and OMC established prior to 1996; and (2) increase grain yields when compared with an organic forage-based cropping system. Furthermore, we hypothesized that (3) the conventional cropping systems will have greater grain yields than either organic cropping system; (4) in years of less than average rainfall, yields will decrease less in cropping systems with high soil OMC; and (5) grain yields will increase with soil P and OMC.

Materials and Methods

Cropping systems

The Long-Term Crop Rotation experiment was initiated in 1975 at the University of Nebraska ARDC near Mead, NE, and redesigned in 1996 to evaluate the productivity of two organic and two conventional cropping systems that differ in crop diversity, pest management and nutrient input strategies. Dominant soil type at the site is a Sharpsburg silty clay loam (fine, smectitic, mesic Typic Argiudoll) with 0–5% slopes[7]. Total area of the study site is 4 ha and has been managed without irrigation.

The experiment was designed as a randomized complete block with four replicate blocks and 13 experimental units per block. From 1975 to 1995 (stage one) the treatments included continuous corn with synthetic fertilizer and herbicides (HFI CC), a 4-year rotation with synthetic fertilizer and herbicides (HF, corn–soybean–corn–oat/clover), the same four-year rotation with manure only (ORG), and the same 4-year rotation with only synthetic fertilizers (FO). The four cropping systems established within each block in 1996 (stage two) included: conventional (CR; to replace HFI CC), diversified conventional (DIR; to replace HF), organic animal manure-based (OAM; to replace ORG) and organic forage-based (OFG; to replace FO). While the management practices and cropping systems differ between the two stages of the experiment, soil analyses were conducted at the conclusion of stage one to document initial differences in soil properties attributed to management during stage one of the long-term experiment. The current DIR, OAM and OFG systems are replicated four times within each block so that each crop phase of the four-year crop sequence is present each year within each block. The CR system is present in only one experimental unit per block with a single-crop phase. Each experimental unit in the original study was 0.047 ha (12.2 m × 38.4 m), and was split into half in 1996 to create two sequences within each crop rotation to include sorghum in the cereal phase of each rotation. In 1996, sorghum was an important agronomic crop in Nebraska representing 1.25 million acres of annual production[21]. Moreover, it was hypothesized that including sorghum in the rotations would increase the economic resilience of the systems, and potentially reduce weed populations through allelopathic interactions.

Table 1. Rotational sequences for each cropping system in stage two of the Long-Term Crop Rotation experiment at the University of Nebraska–Lincoln Agricultural Research and Development Center near Mead, NE. Cropping systems include conventional (CR), diversified conventional (DIR), organic animal manure-based (OAM) and organic forage-based (OFG).

System	Sequence	1st year	2nd year	3rd year	4th year
CR	1	Corn	Soybean	Sorghum	Soybean
	2	Sorghum	Soybean	Corn	Soybean
DIR	1	Corn	Sorghum	Soybean	Wheat
	2	Sorghum	Corn	Soybean	Wheat
OAM	1	Soybean	Corn	Soybean	Wheat
	2	Soybean	Sorghum	Soybean	Wheat
OFG	1	Alfalfa	Alfalfa	Corn	Wheat
	2	Alfalfa	Alfalfa	Sorghum	Wheat

Detailed crop rotation and sequences for the four cropping systems are summarized in Table 1. Cropping systems and rotation sequences were designed based on the input of a farmer advisory panel, which also advised on common cultural practices among conventional and organic farmers in eastern Nebraska prior to the 1996 growing season. The 'systems-based' experimental approach provided flexibility in the design of realistic organic and conventional cropping systems. Each of these rotations was built around corn and sorghum, as grain crop production dominates the eastern Nebraska landscape[21]. These two crops are present in all four rotations to allow for a common comparison among all systems, while soybean and winter wheat are present in at least one organic (OAM or OFG) and one conventional (CR or DIR) system to allow for comparison between organic and conventional systems in general.

Alfalfa was included in the OFG system because it represents a valuable commodity for livestock production, and is also seen as a potentially low-input crop well suited to organic production. While this commodity is traditionally utilized on-farm, it is not uncommon to export high-quality alfalfa hay from the farm (e.g., dairy farms, feedlots and ranches). The grain crops in the OAM system rely exclusively on animal manure for nutrient inputs, which is not an unrealistic option for most farmers in eastern Nebraska as there is an abundance of cattle feedlot operations[21]. Of course, an integrated crop–livestock operation would have the added flexibility of feeding a forage crop on-farm and recycling those nutrients through a free on-farm manure source. However, as farming operations become less diverse and more specialized in crop or livestock production, the reality of exporting nutrients (in the form of feed or manure) from the farm is increasingly common[22].

Corn and sorghum

In the CR and DIR systems, each spring corn and sorghum experimental unit was fertilized with an average of 120 kg N ha^{-1} (as urea, ammonium nitrate, liquid N or anhydrous ammonia), and an average of 40 kg P ha^{-1} (broadcast applied as dry superphosphate between 1997 and 1999). Annual fertilizer application rates were determined after consideration of soil tests from select experimental units (i.e., few experimental units sampled with insufficient sample size for statistical analysis), realistic crop yield goals and University of Nebraska recommendations[23]. In most years, seedbed preparation consisted of disking and/or field cultivation. Average corn seeding rate was 57,300 seeds ha^{-1} and average sorghum seeding rate was 321,000 seeds ha^{-1}. Weed management for corn and sorghum in the conventional systems included a diverse selection of pre- (PRE) and post-emergence (POST) herbicides combined with two inter-row cultivations.

Corn and sorghum in the OAM system were amended with an average of 31.7 Mg ha^{-1} (dry matter basis hereafter) of semi-composted bovine manure, while the OFG system received just one 31.3 Mg ha^{-1} application of semi-composted bovine manure in 1996 to alleviate potential P deficiency (Table 2). Based on a 12-year average analysis of the bovine feedlot manure source utilized in the organic systems, total N content was 1.16%, total P content was 0.68% and total K content was 2.43% (Table 2). Manure was broadcast applied and incorporated with a field disk in the spring. Similar to the synthetic fertilizer rates, manure application rates for all crops were determined after consideration of soil tests from select experimental units within each system, and realistic crop yield goals. However, manure application rates in the OAM system were based on crop N demands, while rates in the OFG system were typically based on potential P deficiency in subsequent crops. Between 1997 and 1999, a hairy vetch (*Vicia villosa*) living mulch was included during the corn and sorghum phase of the OFG system (34 kg ha^{-1} broadcast seeding rate; approximately 1.1 million seeds ha^{-1}). Hairy vetch seed was broadcast with hand-held spreaders during early vegetative growth of corn and sorghum. However, this practice was discontinued after 1999 due to poor establishment and growth of the hairy vetch. Both organic systems were disked and field cultivated each spring for seedbed preparation. The seeding rates for corn and sorghum in the organic systems were the same as those in the conventional systems. Weed management for corn and sorghum in the organic systems included an average of three early cultivations with a rotary hoe and two inter-row cultivations.

Corn was typically planted between late-April and mid-May in 0.76 m rows, while sorghum was planted mid- to late-May in 0.76 m rows. Corn hybrids planted include: Hoegemeyer Hybrids (Hooper, NE, USA) '2591', '2598', '2647', '2648', '2649', '2680' and '2693'; NC+ (Lincoln, NE, USA) '3448', '40M21', '54M52' and '69R36'; Pioneer (Johnston, IA, USA) '3751'; DeKalb (Thomasboro, IL, USA) '646'; and 33 different hybrids from Blue River Hybrids (Kelley, IA, USA). Between 2004 and 2007 CR and OAM experimental units were utilized in a genotype by system variety trial using Blue River Hybrids corn and soybean. These experimental units were divided into 15

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Table 2. Year, cropping system, crop phase, rates and nutrient analysis (dry matter basis) for semi-composted bovine feedlot manure applications utilized in the OAM and OFG systems between 1996 and 2007 in the Long-Term Crop Rotation experiment near Mead, NE. Year is relative to a given crop phase, not the actual application (e.g., 2002 OFG-A had manure applied in the fall of 2001, but is intended for crop uptake during the 2002 crop phase). OAM, organic animal manure-based system; OFG, organic forage-based system; CS, corn/sorghum phase; WW, winter wheat phase; A, alfalfa phase.

Year System-phase	N	P	K	Application rate
	--------%--------			----$Mg\,ha^{-1}$----
1996				
OAM–CS	1.76	0.77	4.00	13.1
OFG–CS	1.76	0.77	4.00	32.4
OAM–WW	0.88	0.29	2.47	38.0
OFG–A	0.92	1.19	2.46	31.3
1997				
OAM–CS	0.94	0.55	2.49	25.3
OAM–WW	1.27	0.66	2.29	20.8
1998				
OAM–CS	0.68	0.82	–	58.5
OAM–WW	0.68	0.82	–	5.8
1999				
OAM–CS	0.59	0.54	2.47	80.7
OAM–WW	5.66	0.35	2.37	44.8
OFG–A	0.85	0.79	3.41	60.6
2000				
OAM–CS	0.41	0.50	2.61	19.7
OAM–WW	0.41	0.50	2.61	38.8
OFG–A	0.55	0.45	2.82	57.3
2001				
OAM–CS	1.36	0.97	2.15	23.0
OAM–WW	1.36	0.97	2.15	20.0
OFG–A	0.41	0.50	2.61	35.4
2002				
OAM–CS	1.74	0.46	2.81	44.6
OAM–WW	0.61	0.62	1.31	12.1
OFG–A	0.61	0.62	1.31	45.2
2003				
OAM–CS	1.13	0.54	1.30	22.8
OAM–WW	1.13	0.54	1.30	22.8
2004				
OAM–CS	1.13	1.22	1.57	25.9
2005				
OAM–CS	1.46	0.87	2.61	14.9
OFG–A	1.46	0.87	2.61	20.2
2006				
OAM–CS	0.98	0.60	2.53	25.7
2007				
OAM–CS	0.60	0.47	2.51	25.9

sub-plots and grain yield for this study was reported as the average of all 15 sub-plots. Genotypes tested in this variety trial represented competitive and modern hybrids/varieties for eastern Nebraska; thus, the range of yield differences among genotypes within systems was reasonably small (unpublished data). Compiling the average yield for these genotypes was seen as the most representative sample of yield for the entire experimental unit. Sorghum varieties planted include: DeKalb '28E', '39Y', '42-20', '53' and '53-11'; NC+ '6B67' and '7R37E'; and Pioneer '87G57'.

Soybean

In the CR and DIR systems, corn and sorghum stalks were shredded each spring and experimental units were disked and/or field cultivated for seedbed preparation. Between 1997 and 2003, soybean in the CR system was planted with a drill in 0.25 m rows at an average rate of 680,000 seeds ha^{-1}, while in 1996 and between 2004 and 2007 soybean was planted in 0.76 m rows at an average rate of 470,000 seeds ha^{-1}. Soybean in the CR system was transitioned out of 0.25 m rows in 2004 to establish the Blue River Hybrids genotype × system variety trial. Soybean in the DIR system was always planted with a drill in 0.25 m rows at an average rate of 642,000 seeds ha^{-1}. Weed management for soybean in the conventional systems included a diverse selection of PRE and POST herbicides combined with one manual roguing operation and two inter-row cultivations when 0.76 m rows were used in the CR system. Glyphosate-resistant soybean varieties were always used in the DIR system and CR system (1997–2003) to allow for POST applications of glyphosate.

In the OAM system, corn and sorghum stalks were shredded each spring and experimental units were disked and field cultivated twice for seedbed preparation. Soybean in the OAM system was planted in 0.76 m rows at an average rate of 470,000 seeds ha^{-1}. Weed management for soybean in the OAM system included an average of three early cultivations with a rotary hoe, two inter-row cultivations and two manual roguing operations.

Timing of soybean planting was typically mid to late May for all systems. Soybean varieties planted include: DeKalb '28-32', and '28-52RR'; Hoegemeyer Hybrids '202', '271RR' and '274'; NC+ '2F11'; Pioneer '9233', '9306', '92B36RR', '92B38RR', '92B61' and '92B63'; UNL Foundation Seed (Ithaca, NE, USA) '3100', 'Conrad', 'Dunbar', 'Hamilton', 'Holt' and 'Resnik'; and 40 varieties from Blue River Hybrids (genotype by system variety trial). Similar to corn experimental units between 2004 and 2007, the CR and OAM soybean experimental units were divided into 15 sub-plots and grain yield for this study was reported as the average of all 15 sub-plots.

Wheat

The DIR system was fertilized with an average of 70 kg $N\,ha^{-1}$ (as ammonium nitrate or liquid N) and 60 kg $P\,ha^{-1}$ (as dry superphosphate). Wheat was planted with a drill in 0.25 m rows at an average rate of 134 $kg\,ha^{-1}$ (approximately 4.5 million seeds ha^{-1}). Weed management for wheat in the DIR system was limited to PRE herbicide applications in 2003 and 2005. Following wheat harvest, wheat stubble and weeds in the DIR system were managed

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with glyphosate application, mowing, disking and/or plowing.

In the OFG system, corn and sorghum stalks were shredded and disked twice for seedbed preparation prior to planting wheat. The OAM system was disked or field cultivated once for seedbed preparation. Each spring between 1996 and 2003 the OAM system was amended with an average of 25.4 Mg ha^{-1} of semi-composted bovine manure (Table 2). This manure was applied over-the-top of the wheat crop and was not incorporated. Wheat in the organic systems was also planted with a drill in 0.25 m rows at an average rate of 134 kg ha^{-1} (approximately 4.5 million seeds ha^{-1}). Following harvest, wheat stubble and weeds in the organic systems were managed with mowing, disking, field cultivation and/or plowing. In six of 12 study years, wheat stubble in the OFG system was amended with an average of 41.7 Mg ha^{-1} of semi-composted bovine manure to alleviate potential P deficiency in the subsequent alfalfa crop (Table 2). These manure applications were incorporated with a disk during simultaneous weed control operations.

For the DIR, OFG and OAM systems, wheat was typically planted between mid October and mid November. Wheat varieties planted include: UNL Foundation Seed '2137', 'Karl', 'Millenium', 'Nekota', 'Wahoo', plus eight additional varieties from UNL Foundation Seed. In 2002 and 2003, all wheat experimental units were utilized in a genotype by system variety trial. Similar to the corn and soybean variety trials, experimental units were divided into eight sub-plots and grain yield for this study was reported as the average of all eight sub-plots in 2002 and 2003.

Alfalfa

Alfalfa was planted at 28 kg ha^{-1} (approximately 12.3 million seeds ha^{-1}) in 0.25 m rows, typically between early August and late September. Alfalfa was cut and baled three times per season and incorporated with a moldboard plow at the end of the second season. Alfalfa varieties planted include: Crow's (Kentland, IN, USA) 'Synergy'; NC+ 'Jade'; and Blue River Hybrids 'Bluebird', 'Jade II' and 'Meadowlark'.

Data collection

There were no records of soil test analyses at the initiation of the experiment in 1975, but it is assumed that the soil nutrient levels of the field were relatively uniform as the field was in continuous alfalfa for three years prior to 1975. Since the beginning of the current cropping systems in 1996, soil samples were taken at the beginning of each 4-year rotation cycle, in early spring of 1996, 2000, 2004 and 2008. Starting in 1996, corn plots were split into half to accommodate equal-sized subplots of corn and sorghum; soil samples were always taken from the corn half of each plot at the beginning of a given cycle. Soil samples were collected to a depth of 122 cm with a tractor-mounted Giddings hydraulic soil coring and sampling machine (Giddings Machine Co., Windsor, CO, USA). Cores were divided into four depths (0–15, 15–61, 61–91 and 91–122 cm), and only the surface depth (0–15 cm) was analyzed in this study. Two samples were taken in random locations within each split-plot experimental unit and pooled to form one composite sample. The sample was mixed by hand and was air dried. A subsample was then boxed without sieving and was delivered to Ward Laboratories Inc. (Kearney, NE, USA) for analysis of soil pH, OMC, P, K, Ca, Mg, Na, SO_4 and Zn. Soil bulk density data were unavailable for each experimental unit; thus, results from the OMC analysis should be interpreted with caution as the integrity of these values depends on the assumption of equal bulk densities within and among treatments.

Soil extraction and analyses were conducted according to routine laboratory procedures at Ward Laboratories Inc. Soil pH was determined using a 1 : 1 soil–water ratio, and OMC was measured as percent oxidizable organic carbon in soil using the Walkley–Black method[24,25]. Phosphorus was extracted by the Bray-1 P test, and the extracting solution consisted of 0.025 M HCl and 0.03 M NH_4F[26]. Potassium (K), Ca, Na and Mg cations were each extracted with 1 N ammonium acetate. The soil and extracting solution were mixed vigorously for 5 min, and the soil was then filtered from the liquid. Individual cation concentrations in the filtrate were analyzed by flame emission in an atomic absorption spectrophotometer[24]. Sulfate was extracted using a calcium phosphate (500 ppm P) extractant. The soil extractant was mixed vigorously for 30 min, and SO_4 concentration in the filtrate was determined by developing a barium sulfate turbidity (determined by flow injection analysis)[24]. Zn was extracted (2 h) with a diethylenetriaminepentaacetic acid (DTPA) chelate solution, which included 0.005 M DTPA, 0.01 M $CaCl_2$ and 0.1 M triethanolamine (TEA) (pH = 7.3)[24].

Growing season precipitation and temperature for corn, sorghum and soybean (April 1–September 30) and winter wheat (October 1–June 15) were determined using the sum of daily precipitation and temperature measurements from the High Plains Regional Climate Center station located on the University of Nebraska Turf Farm near Mead, NE (41°10′12″N lat., 96°28′12″W long., elevation = 366 m), located 1 km northwest of the rotation experiment (Table 3). Climate data for the 30-year mean were obtained from a different climate center near Mead, NE (41°8′24″N and 96°28′48″W) between 1971 and 2000 (long-term data from the University of Nebraska Turf farm were unavailable).

Grain crop yield was measured by harvesting the middle 4.6 m × 38.4 m in each experimental unit, transferring the combine contents into a weigh wagon and measuring grain moisture content in the laboratory with a GAC 2100 grain moisture tester (DICKEY-john Grain Instrumentation, Ankeny, IA, USA). Corn grain yields were adjusted to 0.155, sorghum to 0.140 and soybean and wheat to 0.130 g kg^{-1} moisture. Alfalfa yield was measured by collecting three biomass samples from three separate

Table 3. Annual growing season precipitation and temperature values for summer annual (April 1–September 30) and winter annual (October 1–June 15) crops between 1996 and 2007 measured 1 km northwest of the Long-Term Crop Rotation Experiment near Mead, NE. The 30-year mean represents the mean precipitation and temperature near Mead, NE (41°8′24″ N and 96°28′48″ W) between 1971 and 2000.

	Precipitation (mm)		Temperature (°C)	
Year	**April 1–September 30**	**October 1–June 15**	**April 1–September 30**	**October 1–June 15**
1996	499	355	18.0	4.7
1997	378	189	18.1	5.7
1998	530	566	20.1	7.3
1999	600	463	18.8	7.2
2000	401	226	19.6	6.5
2001	452	531	19.6	6.9
2002	470	337	19.8	6.4
2003	363	367	18.6	6.0
2004	451	444	18.6	6.6
2005	397	424	19.9	6.8
2006	506	335	19.6	7.7
2007	610	524	19.6	6.0
Study mean	471	397	19.2	6.5
30-year mean	519	411	19.0	5.8

windrows (harvest area of 1.52 m × 4.88 m), drying at 60°C to constant mass, and weighing. In 1997, wheat was harvested for hay (due to severe drought and broadleaf weed pressure) and yield was determined using the alfalfa yield determination method.

Statistical analysis

Every 4 years of a rotation was considered a full cycle and within a given cycle there were four crop phases. For example, cycle one included crops grown between 1996 and 1999, while crop phase one included crops grown in 1996, 2000 and 2004 in a given experimental unit and crop phase two included crops grown in 1997, 2001 and 2005, etc. Therefore, between 1996 and 2007 there were three complete rotation cycles and four crop phases within each cycle. This analysis allows comparison of each crop at the same point in each rotation sequence. This experimental design is a split-plot over time, with cropping system (e.g., OFG) as the whole plot and year/current crop (e.g., 1999 corn) as the split-plot[7]. Soil sampling always occurred in the corn half (sequence 1) of all experimental units during crop phase one of each rotation cycle; thus, statistical analysis involving soil properties did not include crop phase or sequence as fixed effects.

While the CR system was only present in one whole plot experimental unit per block, comparisons with the three other systems were still possible within each crop phase for corn, sorghum and soybean. For example, in 1996 corn and sorghum split-plots were present in CR blocks 1 and 3 (crop phases 1 and 3 are present in both blocks due to split-plot experimental units), while soybean was present in CR blocks 2 and 4 (crop phases 2 and 4). Crop phases 2 and 4 were eventually pooled for analysis due to the lack of differences following corn (crop phase 1) and sorghum (crop phase 3). Thus, yield means in the CR system were available for comparison in all years, but the variance was inflated due to the reduced number of replications (two for corn, sorghum and soybean phases) in this system.

Analysis of variance was conducted to determine differences in individual crop yield. Fixed effects in the model included crop phase, system, year(crop phase) (crop phase 'nested' within year due to the dependence of crop phase on year), sequence, and the two-way interactions of crop phase × system, and year(crop phase) × system. Random effects included block (crop phase) and the interactions of system × block(crop phase) and year × block(crop phase) (PROC MIXED; SAS Version 9.1, SAS Inst., Cary, NC, USA). Yields were then pooled by crop phase, sequence and year within systems and compared using orthogonal contrasts. Similarly, analysis of variance was used to determine the effect of growing season precipitation on crop yield; this model was identical to the model outlined above except that growing season precipitation replaced year as a fixed effect and crop phase was not nested within the effect of precipitation. Crop phase and sequence were again pooled within systems and compared using orthogonal contrasts.

Analysis of variance was also used to assess the effects of system, OMC and P on crop yield. Fixed effects in this model included system, OMC, P and the two-way interactions of system × OMC and system × P. Block and the block × system interaction were the random effects in the model. Lastly, differences in individual soil properties were determined with analysis of variance where system, previous crop and year were considered fixed effects and block and the block × system interaction were the random effects in the model. Previous crops were then pooled

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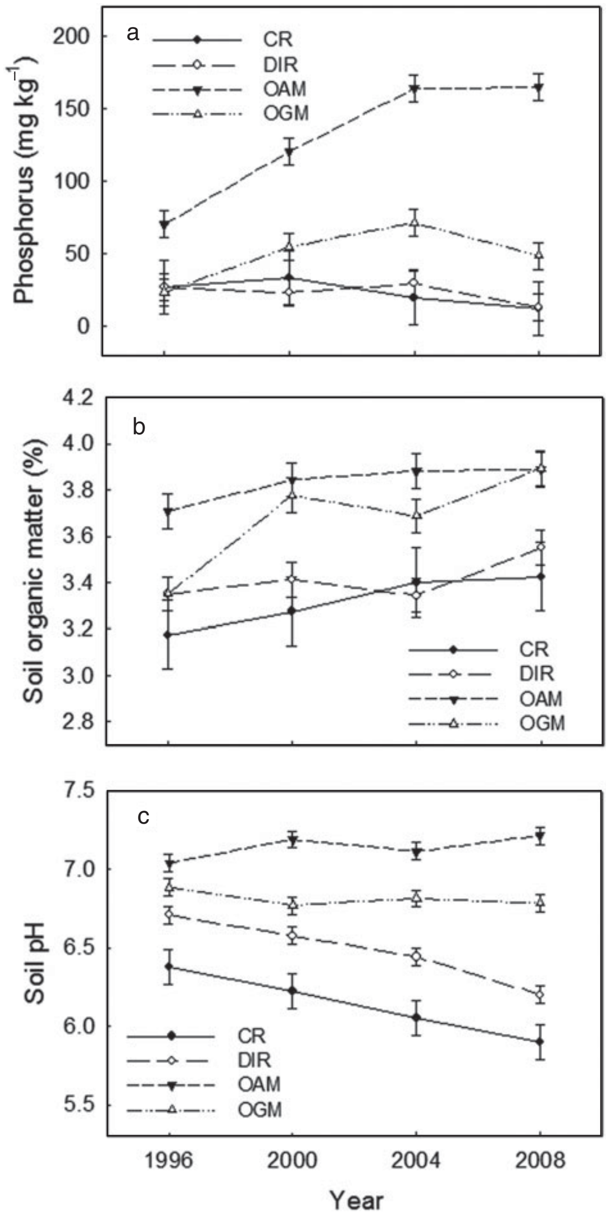

Figure 1. Soil (a) P (Bray-1 P), (b) soil OMC (%), and (c) pH sampled to a depth of 15 cm in conventional (CR), diversified conventional (DIR), organic animal manure-based (OAM), and organic forage-based (OFG) systems between 1996 and 2008 from the Long-Term Crop Rotation experiment near Mead, NE. Bars represent the standard error of the mean.

within systems and compared using orthogonal contrasts. A significance level of $\alpha = 0.05$ was chosen to indicate the statistical difference in all analyses.

Results and Discussion

Soil properties

Measurements of soil pH, OMC, P and K taken between 1979 and 1990 were reported by Lesoing[7]. After four cycles of the rotation (measured in the fall of 1990), soil OMC was greater in the organic treatment (3.84%) compared with the average of the three conventional treatments (3.27%), and P and K values in the organic treatment were 4.5 and 1.6 times greater, respectively, than the average of the three conventional treatments after 16 years since the field came out of uniform alfalfa[7]. These values are reported for experimental site historical reference and could not be statistically analyzed.

After 1996, many soil chemical and physical properties were affected by nutrient source and time. In 2004 and 2008, P concentrations were greater in soils receiving manure amendments (OAM and OFG) compared with soils receiving synthetic P fertilizer (CR and DIR) (Fig. 1a). Soils in the OAM system, which have received biennial manure amendments since 1975, had greater P concentrations than other systems between 1996 and 2008, confirming trends established in the first four cycles[7]. When comparing the 1996 and 2008 soil analyses, P concentrations remained stable in the CR and DIR systems, whereas concentrations increased in the OAM system (70–165 mg P kg^{-1}). The P levels in the OFG system were not different when comparing 1996 and 2008 results, but P levels did increase in this system in both 2000 and 2004, relative to 1996 levels. While 2008 P concentrations within the CR, DIR and OFG systems did not change relative to their respective 1996 levels, the gap between the conventional systems (slight reduction in P) and OFG system (slight increase in P) widened enough that by 2004 and 2008 P concentrations were statistically greater in the OFG system. Similarly, OMC was greater in soils with animal manure amendments (OAM and OFG; Fig. 1b). While OMC was relatively stable in the CR, DIR and OAM systems, the OFG system experienced an increase in OMC from 1996 to 2008 (3.35–3.89%). Across all years, soil pH was greatest in the OAM system, followed by OFG, DIR and CR. Over time, soils amended with synthetic fertilizers became more acidic (CR soils decreased from pH 6.38 in 1996 to 5.90 in 2008; DIR soils decreased from pH 6.71 in 1996 to 6.20 in 2008), while soils amended with manure became more alkaline (OAM soils increased from pH 7.04 in 1996 to 7.21 in 2008) or remained stable (OFG soil pH was 6.88 in 1996 and 6.78 in 2008) (Fig. 1c). The increased levels of soil P, OMC and pH in the OAM system support hypothesis 1.

In further support of hypothesis 1, soil levels of Ca, K, Mg and Zn were generally greater in cropping systems amended with animal manure between 1996 and 2008 (OAM and OFG; Table 4). Calcium levels were greater in manure-amended systems compared with synthetically amended systems in each of the four sampling years. DIR was the only system that experienced decreased levels of Ca, whereas the other three systems remained stable between 1996 and 2008. K levels were consistently greatest in the OAM system in each of the four sampling years. Soils in the OFG system contained the second-greatest K levels between 2000 and 2008. K levels increased between 1996 and 2008 in both the OAM and OFG systems, while concentrations remained stable in plots amended with synthetic fertilizers. Similarly, Mg levels were greatest in

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Table 4. Soil fertility measurements taken between 1996 and 2008 from stage two of the Long-Term Crop Rotation experiment near Mead, NE. All soil samples were collected to a depth of 15 cm. CR, conventional; DIR, diversified conventional; OAM, organic animal manure-based; OFG, organic forage-based. Different letters following values within a given year and soil nutrient indicate a significant difference ($P < 0.05$).

	Year							
Soil property	**1996**		**2000**		**2004**		**2008**	
	------------cmol kg^{-1}------------							
Calcium								
CR	11.04	b	11.28	b	9.96	b	9.80	b
DIR	12.18	b	12.48	b	11.36	b	11.13	b
OAM	13.21	a	13.72	a	12.80	a	13.05	a
OFG	13.26	a	13.70	a	13.03	a	12.69	a
Potassium								
CR	0.90	b	0.90	c	1.08	bc	0.97	bc
DIR	0.95	b	1.03	c	1.05	c	0.95	c
OAM	1.41	a	1.76	a	2.01	a	1.74	a
OFG	0.91	b	1.32	b	1.24	b	1.23	b
Magnesium								
CR	2.98	abc	2.73	b	2.59	b	2.69	b
DIR	2.96	bc	2.99	b	2.83	b	2.90	b
OAM	3.38	a	3.63	a	3.53	a	3.62	a
OFG	3.33	ab	3.43	a	3.45	a	3.48	a
Sodium								
CR	0.21	a	0.09	a	0.08	b	0.09	a
DIR	0.15	b	0.09	a	0.10	b	0.10	a
OAM	0.13	b	0.11	a	0.14	a	0.11	a
OFG	0.16	ab	0.10	a	0.12	ab	0.10	a
	-------------mg kg^{-1}-------------							
Sulfate								
CR	10.50	a	11.75	b	12.00	b	12.50	a
DIR	10.50	a	10.94	b	11.19	b	11.38	a
OAM	11.69	a	15.31	a	16.25	a	12.44	a
OFG	11.31	a	15.06	a	13.56	b	12.56	a
Zinc								
CR	0.85	ab	1.02	b	1.04	c	0.88	bc
DIR	0.85	b	1.58	b	0.97	c	0.75	c
OAM	1.87	a	2.71	a	3.83	a	3.24	a
OFG	0.79	b	1.42	b	2.19	b	1.50	b

the organic systems between 2000 and 2008. In 1996, Mg levels were greatest in the OAM system. Between 1996 and 2008, Mg levels remained stable in all systems. Zn levels were greatest in the OAM system between 2000 and 2008. In 1996, levels of Zn in the OAM system were greater than levels in the DIR and OFG system, but not the CR system. Between 1996 and 2008, Zn levels increased in the organic systems and remained stable in the conventional systems (CR and DIR). Soil levels of Na and sulfate were inconsistent among systems and over time. However, Na levels generally decreased across all treatments between 1996 and 2008.

Soil fertility in organic production systems is maintained with organic amendments such as farmyard manure and including forage legumes (e.g., alfalfa) and green manures in the crop rotation[27]. In this long-term experiment, differences in soil properties were likely due to differences in crop sequence, soil amendments, frequency of tillage and nutrient inputs among cropping systems (Tables 5–7). Phosphorus, OMC, pH, Ca, K, Mg and Zn were all greater in soils amended with manure (OAM and OFG) compared to soil amended with synthetic fertilizers (CR and DIR). Greater concentrations of P, OMC, Ca, K and Mg in organically amended soils have been observed in many previous studies[15,16,27,30]. However, despite the lack of K inputs and subsequent negative nutrient budgets in both the CR and DIR systems (−0.53 and −0.41 cmol K kg^{-1}, respectively), K levels did not change in the conventional systems between 1996 and 2008 (Table 5). Indeed, K fertilizer application in eastern Nebraska soils is rare and in some cases can result in grain yield reductions[31]. In most situations, sufficient background soil levels combined with K supplied from the organic matter fraction is sufficient for the sustainable maintenance of long-term cropping systems in eastern Nebraska[32]. The general reduction of Na over time in organically amended soils of this study is unique, given that the application of animal manure often leads to salinity problems in soil[33]. This reduction in Na may be attributed to the presence of sorghum in all systems since 1996, as sorghum has demonstrated high Na removal efficiency and can be used in the reclamation of sodic soils[34].

It is interesting to note that soil P levels remained relatively stable in the OFG system between 1996 and 2008, despite a substantial surplus in the P nutrient budget for this system (Table 6). Indeed, at least two previous studies have demonstrated a negative P balance when alfalfa is included in rotation[18,19]. However, another study found that continuous alfalfa production increased the soil organic P fraction compared with grain-based annual cropping systems[35]. It is possible that stable P is extracted from the soil by alfalfa roots and transformed into a more labile form upon root death[35]. Moreover, alfalfa serves as a host to arbuscular mycorrhizal fungi, which have been shown to increase the availability and uptake of soil P[36]. Despite the potential for increased soil P availability associated with alfalfa production, the removal of P in the form of multiple hay cuttings contributed to relatively low levels of soil P in the OFG system, considering the surplus of P inputs via animal manure (Table 6). As expected, frequent manure application to meet grain crop N demands resulted in a substantial surplus of soil P in the OAM system (Table 6 and Fig. 1a). Similar to K, soil P levels did not change between 1996 and 2008 in the conventional systems despite infrequent fertilizer application and subsequently negative nutrient balances (−111 mg P kg^{-1} in the CR system and −58 mg P kg^{-1} in the DIR system; Table 6). While background levels of P are not typically as high as background levels of K in eastern Nebraska soils; the release of P from labile organic matter and microbial biomass appeared to compensate for the negative P balances in the conventional systems[32].

Table 5. Farm gate nutrient budget to account for K inputs and outputs within and among cropping systems between 1996 and 2007 in the Long-Term Crop Rotation experiment near Mead, NE. Each crop phase was treated as an equal component (3 years) of the 12-year study period in this budget (e.g., manure was applied 12 times in all OAM corn experimental units between 1996 and 2007, but corn would only be present in 3 of 12 years in a given experimental unit; thus, the total number of applications was divided by 4). OAM, organic animal manure-based; OFG, organic forage-based; CR, conventional; DIR, diversified conventional.

System and crop	Inputs	K content of inputs (%)	Input rate (kg ha^{-1})	No. of applications	Total K input (kg ha^{-1})	K content of crop[1] (%)	Crop yield (kg ha^{-1})	Total K removed[2] (kg ha^{-1})	Total K balance (kg ha^{-1})	Total K balance (cmol kg^{-1})
OAM soybean	None					1.542	1990	92	−92	−0.12
OAM corn	Manure	2.46	31,700	3	2339	0.344	6558	68	2272	3.03
OAM soybean	None					1.542	1990	92	−92	−0.12
OAM wheat	Manure	2.07	25,400	2	1052	0.487	3151	46	1006	1.34
OAM total					**3391**			**298**	**3093**	**4.13**
OFG alfalfa	Manure	2.54	41,700	1.5	1589	2.119	7413	471	1118	1.49
OFG alfalfa	None					2.119	7413	471	−471	−0.63
OFG corn	Manure	4	32,400	0.25	324	0.344	5045	52	272	0.36
OFG wheat	None					0.487	2487	36	−36	−0.05
OFG total					**1913**			**1031**	**882**	**1.18**
CR corn	None					0.344	7379	76	−76	−0.10
CR soybean	None					1.542	2597	120	−120	−0.16
CR sorghum	None					0.415	6364	79	−79	−0.11
CR soybean	None					1.542	2597	120	−120	−0.16
CR total								**396**	**−396**	**−0.53**
DIR corn	None					0.344	7651	79	−79	−0.11
DIR sorghum	None					0.415	6138	76	−76	−0.10
DIR soybean	None					1.542	2369	110	−110	−0.15
DIR wheat	None					0.487	2870	42	−42	−0.06
DIR total								**307**	**−307**	**−0.41**

[1] NRCS Plant Nutrient Content Database[28].
[2] Total K removed = (% K content of grain or forage) × (grain or forage yield) × (3 years in rotation per experimental unit).

In this study, we observed greater pH in soils receiving organic amendments compared with soils receiving synthetic fertilizers, which is consistent with the results of several previous studies[16,37,38]. Moreover, the reduction in soil pH in the conventional systems over time is congruent with the results of another long-term cropping systems experiment conducted at the ARDC near Mead, NE where soil pH decreased as synthetic N rate increased[39]. In a similar long-term rotation study, the pH of soils in organic and 'zero-input' rotations was greater than pH levels in a 'high-input' corn–soybean rotation[2]. Addition of organic amendments may raise the pH of soils by complexing aluminum and increasing base saturation[40,41]. The calcium carbonate excreted in animal manure serves as a liming source in soils, often raising soil pH. When manure is applied in high quantities to meet crop N demand soil pH has been shown to increase, whereas manure application to meet crop P demand has been shown to stabilize soil pH[42]. These findings are consistent with the results of this study where soil pH increased over time in the OAM system (manure applied to meet crop N demand) and remained stable in the OFG system (manure applied to meet crop P demand). The reduced soil pH over time in the conventional systems was likely the result of synthetic fertilizer application. While few synthetic fertilizers are actually acidic, many are acid forming. This soil acidification is most often caused by microbial oxidation of ammoniacal fertilizers resulting in nitric acid accumulation. Much of the excess nitric acid is then stored in organic matter and the soil pH decreases[43].

The results of this study are in contrast to those found in several European experiments that have demonstrated negative nutrient balances and decreasing pH values in organic cropping systems. For example, Eltun et al.[44] reported an increasingly negative nutrient balance for P and K in organic arable and forage cropping systems, despite organic amendments. Moreover, Breland and Eltun[45] concluded that arable cropping systems (dominated by annual cereals) have poorer soil fertility than forage-based systems. The OFG system in this study included 2 years of forage within each 4-year cycle, but the nutrient levels in the OAM system were still greater than those in the OFG system. Kirchmann et al.[4] and Gosling and Shephard[9] reported lower pH values in organically managed soils compared with those amended with synthetic fertilizer. Crop rotations that rely heavily on legumes for symbiotic nitrogen fixation may acidify soils because legumes release more protons from their roots than non-legume cereal crops[46]. Both organic rotations in this study included a leguminous crop (soybean or alfalfa) in 2 of the 4 years of each cycle; however, soil pH remained stable (OFG) or increased (OAM) between 1996 and 2008. Contradictory

Table 6. Farm gate nutrient budget to account for phosphorus inputs and outputs within and among cropping systems between 1996 and 2007 in the Long-Term Crop Rotation experiment near Mead, NE. Each crop phase was treated as an equal component (3 years) of the 12-year study period in this budget. OAM, organic animal manure-based; OFG, organic forage-based; CR, conventional; DIR, diversified conventional.

System and crop	Inputs	P content of inputs (%)	Input rate ($kg\,ha^{-1}$)	No. of applications	Total P input ($kg\,ha^{-1}$)	P content of crop[1] (%)	Crop yield ($kg\,ha^{-1}$)	Total P removed[2] ($kg\,ha^{-1}$)	Total P balance ($kg\,ha^{-1}$)	
									($kg\,ha^{-1}$)	($mg\,kg^{-1}$)
OAM soybean	None					0.659	1990	39	−39	−20
OAM corn	Manure	0.693	31,700	3	659	0.317	6558	62	597	311
OAM soybean	None					0.659	1990	39	−39	−20
OAM wheat	Manure	0.595	25,400	2	302	0.435	3151	41	261	136
OAM total					**961**			**182**	**779**	**406**
OFG alfalfa	Manure	0.737	41,700	1.5	461	0.261	7413	58	403	210
OFG alfalfa	None					0.261	7413	58	−58	−30
OFG corn	Manure	0.77	32,400	0.25	62	0.317	5045	48	14	7
OFG wheat	None					0.435	2487	32	−32	−17
OFG total					**523**			**197**	**327**	**170**
CR corn	Phosphate	46	40	3	13.8	0.317	7379	70	−56	−29
CR soybean	None				0	0.659	2597	51	−51	−27
CR sorghum	Phosphate	46	40	3	13.8	0.352	6364	67	−53	−28
CR soybean	None				0	0.659	2597	51	−51	−27
CR total					**27.6**			**240**	**−212**	**−111**
DIR corn	Phosphate	46	40	0.75	13.8	0.317	7651	73	−59	−31
DIR sorghum	Phosphate	46	40	0.75	13.8	0.352	6138	65	−51	−27
DIR soybean	None					0.659	2369	47	−47	−24
DIR wheat	Phosphate	46	60	3	82.8	0.435	2870	37	45	24
DIR total					**110.4**			**222**	**−111**	**−58**

[1] NRCS Plant Nutrient Content Database[28].
[2] Total P removed = (% P content of grain or forage) × (grain or forage yield) × (3 years in rotation per experimental unit).

results on this issue suggest the continued importance of monitoring soil pH and mineral nutrients in conventional and organic systems. Organic farmers face greater limitations when dealing with soil mineral deficiencies since they cannot apply synthetic fertilizers; thus, the maintenance of soil fertility through system design is essential to the long-term sustainability of organic cropping systems[44].

In a 21-year long-term trial, nutrient inputs were 34–51% lower in organic systems compared with conventional systems, while yields in organic systems were only 20% lower[37]. This may suggest crops in organic systems utilize nutrients more efficiently than the same crops in conventional systems. An apparent increase in nutrient-use efficiency may be the result of increased mineralization of OMC in organic cropping systems. Moreover, soil OMC is widely recognized as a key indicator of soil quality[47]. Total organic carbon concentration (TOC), a measure of OMC, increased by 9% in the top 15 cm of the soil after 4 years of organic management in Iowa, while TOC in conventionally managed plots increased by only 3%[27]. In a summary of long-term trials across the US, both 'legume-only' and 'legume + animal manure' organic systems increased soil organic carbon (SOC) by 14% compared with conventional systems after an average of 10 years[14]. Similarly, Kirchmann et al.[4] reported greater SOC in organic systems compared with conventional. However, this was a result of 40% greater carbon inputs in the organic system; the organic system included solid manure, cover crops and greater weed residue for incorporation[4]. Therefore, the greater levels of OMC observed in the OAM and OFG systems are likely due to the greater amount of carbon inputs (e.g., bovine manure, alfalfa, weed residue; Table 7). Regardless of carbon inputs, the results of this study are congruent with previous findings in that OMC was 10% greater in the organic systems compared to the conventional systems as of 2008. However, in the absence of soil bulk density data, we cannot eliminate the possibility that differences in OMC among systems were due in part to differences among cropping systems in soil bulk density. Indeed, the variable management strategies (e.g., tillage intensity and manure application) associated with each system may have led to changes in soil bulk density[48].

One study revealed greater levels of total soil carbon in organic legume systems (without animal manure inputs) compared to conventional systems after 20+ years of arable farming[12]. This is significant because estimates of net annual soil carbon inputs were similar for the two systems[3]. Drinkwater et al.[12] demonstrated that the use of low C : N residue (e.g., legumes) to maintain soil fertility, coupled with greater temporal diversity of crop rotations, can increase the retention of soil carbon. Therefore, the soil OMC in the organic systems of this study may have increased over time due to a combination of increased carbon inputs and the inclusion of low C : N crop residue.

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Table 7. Carbon inputs within and among cropping systems between 1996 and 2007 in the Long-Term Crop Rotation experiment near Mead, NE. Each crop phase was treated as an equal component (3 years) of the 12-year study period in all calculations. OAM, organic animal manure-based; OFG, organic forage-based; CR, conventional; DIR, diversified conventional.

System and crop	Inputs	Manure C content (%)	Manure rate[1] ($kg\,ha^{-1}$)	Crop residue C content[2] (%)	Crop yield ($kg\,ha^{-1}$)	Harvest index[2] (%)	Weed input[3] ($kg\,ha^{-1}$)	Weed C content[2] (%)	Total C input[4] ($kg\,ha^{-1}$)
OAM soybean	None			15	1990	46	2024	25	2002
OAM corn	Manure	10	31,700	30	6558	52	2488	25	33,229
OAM soybean	None			15	1990	46	2024	25	2002
OAM wheat	Manure	10	25,400	50	3151	51	192	25	17,700
OAM total									**54,932**
OFG alfalfa	Manure	10	41,700	32.5	7413	100	0	25	18,765
OFG alfalfa	None			32.5	7413	86.5	0	25	976
OFG corn	Manure	10	32,400	30	5045	52	3715	25	7396
OFG wheat	None			50	2487	51	729	25	2375
OFG total									**29,511**
CR corn	None			30	7379	52	64	25	3236
CR soybean	None			15	2597	46	93	25	701
CR sorghum	None			40	6364	49	188	25	4036
CR soybean	None			15	2597	46	93	25	701
CR total									**8673**
DIR corn	None			30	7651	52	291	25	3523
DIR Sorghum	None			40	6138	49	233	25	3931
DIR soybean	None			15	2369	46	15	25	587
DIR wheat	None			50	2870	51	216	25	2271
DIR total									**10,313**

[1] Total manure C input based on manure rate and application frequency data from Tables 5 and 6.
[2] Assumed values.
[3] Aboveground weed biomass (Wortman et al.[29]).
[4] Total C input = (((% manure C content) × (manure rate) × (no. of applications per crop phase per 12 years)) + ((% crop residue C content) × (grain or forage yield) × (1 − (% harvest index))) + ((% weed residue C content) × (weed residue input))) × (3 years in rotation per experimental unit).

The rotation in the OAM system included 2 years of soybean and the rotation in the OFG system included 2 years of alfalfa (both legumes with low C : N ratios). In another study, OMC decreased an average of 2% annually in an annual crop/plowed system, indicating the importance of forage crops for the maintenance of OMC[17]. Including forage crops in the rotation (at least 50%, as in the OFG system) can also increase soil stability, soil porosity and available soil water[17]. The soil-building benefits of forage crops combined with the reduction of tillage during this crop phase may help explain the similar levels of soil OMC in the OAM and OFG systems, despite fewer carbon inputs in the OFG system. In 2008, OMC was not different between the OAM and OFG systems despite approximately 46% greater carbon inputs in the OAM system (Table 7). Tillage consistently reduces levels of soil OMC compared to no-till practices[49]; thus, the lack of tillage during the 2-year alfalfa phase in the OFG system may have negated the greater carbon inputs in the OAM system with regard to building soil OMC.

Overall, it seems that manure application in the organic systems is more effective in building soil P than OMC. Manure application rates in the OAM system were based on subsequent crop N demands, which often results in the accumulation of soil P because the N : P ratio of the manure source is usually smaller than the N : P ratio of crop uptake, as was the case in this study (Table 2)[50]. Moreover, while manure is a substantial source of organic carbon and should increase soil OMC, the extensive use of tillage in the organic systems will result in the accelerated microbial oxidation of this carbon source[51].

While it may not be possible to determine mechanistic differences among systems due to varying management practices between the conventional and organic systems (e.g., manure application in the organic systems), it is clear that organic cropping systems with manure amendments appear to increase soil nutrients, soil pH and OMC. Moreover, despite frequent tillage operations organic systems tend to retain greater amounts of soil organic matter[14]. The demonstrated ability of both animal manure- and legume-based organic systems to build soil OMC and maintain soil nutrients indicates great potential for the long-term sustainability of organic farming.

Crop yields

The average daily temperatures during the growing season for summer annual crops (April 1–September 30) and

Table 8. Analysis of variance for the effects of precipitation, system and system × precipitation on yield of each crop between 1996 and 2007 from the Long-Term Crop Rotation experiment near Mead, NE. For corn, sorghum and soybean precipitation values were summed between April 1 and September 30, and for wheat precipitation values were summed between October 1 and June 15.

Crop	Parameter	*P*-value
Corn	System, S	< 0.0001
	Precipitation, P	< 0.0001
	S × P	0.2626
Sorghum	System, S	< 0.0001
	Precipitation, P	0.0059
	S × P	0.6079
Soybean	System, S	< 0.0001
	Precipitation, P	< 0.0001
	S × P	0.0608
Wheat	System, S	< 0.0001
	Precipitation, P	0.0039
	S × P	0.4843

winter wheat (October 1–June 15) between 1996 and 2007 were 19.2 and 6.5°C, respectively (Table 3). These values were warmer than the 30-year mean temperatures (1971–2000) for Mead, NE, which were 19.0 and 5.8°C for summer annual and winter wheat-growing seasons, respectively. The average total precipitation values during the growing season for summer annual crops and winter wheat between 1996 and 2007 were 471 and 397 mm. This was drier than the 30-year mean precipitation values (1971–2000) for summer annual and winter wheat-growing seasons, which were 519 and 411 mm, respectively (Table 3).

Analysis of yield data between 1996 and 2007 indicated a year by cropping system interaction effect for all crops. Annual climatic variation did little to explain these interactions (Table 8); thus, yield data reported here have been averaged across all study years to better understand yield response to the long-term management associated with each cropping system. However, annual yields for each grain crop are presented in Figure 2 to demonstrate this interaction.

From 1996 to 2007, average corn yields were greatest in the DIR (7.65 Mg ha^{-1}) and CR systems (7.38 Mg ha^{-1}), followed by the OAM (6.56 Mg ha^{-1}) and OFG (5.05 Mg ha^{-1}) systems (Fig. 2). In accordance with hypotheses 2 and 3, yields were higher in the OAM system compared with the OFG system, and among all systems yields were greatest in the conventional systems. Both growing season precipitation (April 1–September 30) and system affected corn yield, but in contrast to hypothesis 4 there was no precipitation × system interaction (Table 8). In contrast to hypothesis 5, neither P nor OMC affected corn yield, but there was a significant P × system interaction (Table 9).

From 1996 to 2007, average sorghum yield was greatest in the CR (6.36 Mg ha^{-1}) and DIR systems (6.14 Mg ha^{-1}), followed by the OAM (5.25 Mg ha^{-1}) and OFG (4.59 Mg ha^{-1}) systems (Fig. 2). In accordance with hypotheses 2 and 3, yield was greater in the OAM system compared with the OFG system and among all systems yields were highest in the conventional systems. Both precipitation (April 1–September 30) and system affected sorghum yield, but in contrast to hypothesis 4 there was no precipitation × system interaction (Table 8). In contrast to hypothesis 5, neither P nor OMC affected sorghum yields (Table 9).

From 1996 to 2007, average soybean yield was highest in the CR (2.60 Mg ha^{-1}) and DIR systems (2.37 Mg ha^{-1}) and lowest in the OAM (1.99 Mg ha^{-1}) system (Fig. 2). In accordance with hypothesis 3, yield was greater in the conventional systems compared with the OAM system. Precipitation (April 1–September 30) affected soybean yield, but in contrast to hypothesis 4 there was no precipitation × system interaction (Table 8). OMC did affect soybean yield; however, yield decreased as organic matter increased, which is not consistent with hypothesis 5. Soil P levels did not affect soybean yield (Table 9).

From 1996 to 2007, average wheat yield was greatest in the OAM system (3.15 Mg ha^{-1}), followed by DIR (2.87 Mg ha^{-1}) and OFG (2.49 Mg ha^{-1}) systems (Fig. 2). In accordance with hypothesis 2, yield was greater in the OAM system compared to the OFG system. However, among all systems, yield was greatest in the OAM system which contradicts hypothesis 3. Precipitation (October 1–June 15) affected wheat yield, but in contrast to hypothesis 4 there was no precipitation × system interaction (Table 8). In support of hypothesis 5, soil P levels did affect wheat yields (Table 9). Wheat yields were greatest in the OAM system, which also had the greatest soil P levels. However, in contrast to hypothesis 5, OMC did not affect wheat yields (Table 9).

From 1996 to 2007, average alfalfa forage yields were 7.41 Mg ha^{-1} ± 0.33 Mg ha^{-1} (mean ± one standard error) in the OFG system. This is the only system that included alfalfa therefore yields were compared with the same 12-year county average for conventional alfalfa forage production. The Saunders County, NE (location of ARDC) average during this period for non-irrigated alfalfa hay was 7.64 Mg ha^{-1}, which is not substantially greater than the 12-year yield mean in the OFG system as it falls within one standard error[21].

Several recent studies have demonstrated the competitiveness of long-term organic cropping systems compared with conventional[2,3,6]. While the results of these studies vary by year, crop and climate, the accumulation and comparison of data from around the US will aid in the design of appropriate organic and conventional cropping systems across a diverse range of ecoregions.

Corn is among the most important agronomic crops in the USA; thus, it is commonly included in comparative studies between organic and conventional crop production. In a long-term trial at the Rodale Institute in Pennsylvania, corn grain yields did not differ among organic animal manure-based, organic legume-based and conventional

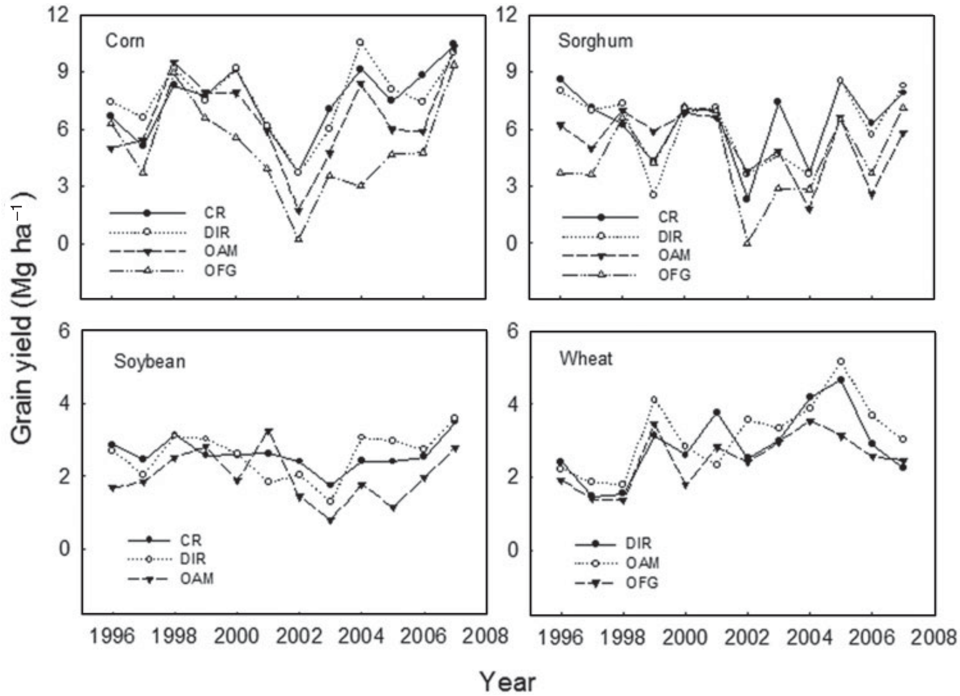

Figure 2. Grain yields for corn, sorghum, soybean and winter wheat in conventional (CR), diversified conventional (DIR), organic animal manure-based (OAM) and organic forage-based (OFG) systems between 1996 and 2007 in the Long-Term Crop Rotation experiment near Mead, NE. Standard errors for annual corn yields were CR ± 0.76 Mg ha^{-1}; DIR, OAM and OGM ± 0.54 Mg ha^{-1}. Standard errors for annual sorghum yields were CR ± 0.55 Mg ha^{-1}; DIR, OAM and OGM ± 0.39 Mg ha^{-1}. Standard errors for annual soybean yields were CR ± 0.44 Mg ha^{-1}; DIR ± 0.31 Mg ha^{-1} and OAM ± 0.22 Mg ha^{-1}. Standard errors for annual wheat yields were DIR, OAM and OGM ± 0.22 Mg ha^{-1}.

production systems[3]. Similarly, Posner et al.[6] and Porter et al.[2] reported organic corn grain yields 91–93% of the conventional system yields in their respective studies. In this study, compared to the average of the two conventional systems (CR and DIR), the OAM system yielded 87% of the conventional corn yields. Less comparable corn yields in organic systems have also been reported. Cavigelli et al.[5] observed organic corn grain yields to be 76% of conventional yields. These results are similar to corn in the OFG system that yielded 67% of the two conventional systems. Sorghum responded similarly to the different management systems; compared with the average of two conventional systems the OAM system yielded 84% and the OFG system yielded 73%. The greater sorghum yields in the OAM system compared to the OFG system are similar to the results of Mady Kaye et al.[10], who observed an 8% increase in sorghum yields when amended with manure and rotated with soybean.

Organic soybean grain yields were much less competitive in this study compared with the results of two recent studies. Posner et al.[6] reported organic soybean yields at 92% of the conventional yields and Pimentel et al.[3] found no difference between organic and conventional soybean yields over a 20-year period (excluding one extreme drought year). In contrast, two other recent studies have reported organic soybean yields in four-year rotations that yielded 81–84% compared with the conventional systems[2,5]. These results are similar to yields observed in this study, where organic (OAM) soybean yields were only 80% of the average of the two conventional system yields. Early season, wet field conditions that limit mechanical weed control, especially rotary hoeing, in organic systems can be particularly damaging to soybean yields[29]. Porter et al.[2] observed organic soybean yields that were only 58 and 69% of conventional yields in unusually wet years, but organic yields between 96 and 99% of conventional yields in 'normal' precipitation years. These results expose the vulnerability of organic cropping systems due to heavy reliance on timely mechanical weed control.

Organic wheat yields seem to be far more competitive with conventional yields than organic corn, sorghum or soybean yields. Organic wheat yields reported by Posner et al.[6] did not differ from the conventional county average. Similarly, organic wheat yields reported by Mader et al.[37] were 90% of conventional yields, and wheat yields reported by Cavigelli et al.[5] were not different between conventional and organic systems. Compared with the conventional system (DIR), we observed greater yields in the OAM system (110%), but reduced yields in the OFG system (87%). Manure application has been identified as an important contributor to improved yields in wheat cropping systems, which may explain the significant yield increase in the OAM system[5,52]. These results suggest winter wheat may be a competitive crop in organic cropping systems in Nebraska, and thus a logical crop choice for organic farmers as an important component of their rotations.

Table 9. Analysis of variance for the effect of system, organic matter content (OMC), phosphorus (P), system × OMC and system × P on yield of each crop in the first crop phase between 1996 and 2004 (1996, 2000 and 2004) from the Long-Term Crop Rotation experiment near Mead, NE.

Crop	Parameter	*P*-value
Corn	System, S	< 0.0001
	Organic matter, OMC	0.7775
	Phosphorus, P	0.2988
	S × OMC	0.2583
	S × P	0.0477
Sorghum	System, S	0.0008
	Organic matter, OMC	0.4581
	Phosphorus, P	0.9488
	S × OMC	0.9527
	S × P	0.4193
Soybean	System, S	0.0157
	Organic matter, OMC	0.0012
	Phosphorus, P	0.4672
	S × OMC	0.9993
	S × P	0.1241
Wheat	System, S	< 0.0001
	Organic matter, OMC	0.7322
	Phosphorus, P	0.0012
	S × OMC	0.8762
	S × P	0.9668

Table 10. Critical soil test values for crops grown in the Long-Term Crop Rotation experiment near Mead, NE according to Ferguson[23].

	Crop				
Soil property	Corn	Sorghum	Soybean	Wheat	Alfalfa
pH	5.1–7.6	5.1–7.7	5.1–7.6	5.1–7.9	5.9–7.9
P ($mg\,kg^{-1}$)	15	15	10	15–25	25
K ($cmol\,kg^{-1}$)	0.32	0.32	0.32	0.32	0.32
Mg ($cmol\,kg^{-1}$)	0.42	0.42	0.42	0.42	0.42
SO_4 ($mg\,kg^{-1}$)	6	6	–	–	5
Zn ($mg\,kg^{-1}$)	0.8	0.8	0.4	–	–

Alfalfa may also be a logical crop choice for organic farmers. In addition to the many soil biological, chemical and physical benefits of growing forages in rotation with grain crops, it seems organic alfalfa yields are also highly competitive with conventional alfalfa yields[2,38]. While alfalfa was only present in the OFG system of this experiment, when compared with the Saunders County, NE conventional average between 1996 and 2007, there was no statistical difference (i.e., the 12-year mean of OFG alfalfa yield ± one standard error includes the 12-year mean of county alfalfa yields). Conventional producers often manage alfalfa with minimal inputs, but growing alfalfa on certified organic land will allow farmers to market the forage as a certified organic product, increasing the profitability of including alfalfa in rotation. However, many farmers are reticent to export a forage crop such as alfalfa from the farm, and prefer to feed livestock to add value to this important resource and minimize export of valuable nutrients from the system.

Many of the yield reductions in the organic systems seem to be the result of increased weed cover and biomass. Porter et al.[2] and Posner et al.[6] reported that in years when mechanical weed control was effective, organic grain yields were equivalent to conventional yields. In effective weed control years, organic corn and soybean yields were 90–98% of conventional yields, but when weed control was not effective organic corn and soybean yields were only 69–80% of conventional yields[6]. These results suggest weed pressure was the major limiting factor in organic corn and soybean production. In 2007 and 2008, we observed greater broadleaf and grass weed biomass in corn and soybean plots of the organic systems compared with the conventional systems[29]. In the absence of nutrient deficiencies, the increased weed biomass is likely responsible for the yield loss observed within the organic systems of this study. While grain yields were generally reduced in the organic systems compared with the conventional systems, lower production costs may increase the economic competitiveness of organic systems even without considering current organic price premiums[2,3]. However, in this long-term study, production costs were similar between conventional and organic systems (data not shown).

Overall, there was no positive effect of OMC on grain yield in any crop. It was hypothesized that increasing OMC would increase crop yield due to the capacity for increased nutrient mineralization and soil water retention[3,14,53,54]. In fact, there was a negative relationship between OMC and soybean yield, which was more likely the result of a positive relationship between OMC and weed biomass in the OAM system ($P < 0.01$; data not shown).

Similarly, there was no positive relationship between soil P and grain yield in any crop except for winter wheat. Phosphorus was maintained near sufficiency levels for corn, sorghum and soybean in all systems, which decreases the likelihood of a positive yield response. However, P sufficiency levels in wheat are greater than those for corn, sorghum and soybean[23] (Table 10). Phosphorus levels in the DIR system were between 12 and 29 $mg\,kg^{-1}$ Bray-1 P throughout the experiment, which may explain the reduced yields in this system compared with the OAM system where Bray-1 P levels were maintained well above sufficiency levels. Moreover, sufficient P nutrition in wheat has been shown to reduce water stress, which may have further contributed to greater yields in the OAM system, especially in dry years[55]. These results suggest that wheat is the most responsive crop to animal manure applications and/or P fertilization, further increasing its usefulness in organic cropping systems. In addition to these benefits, the dense plant spacing and tillering capacity of wheat often results in comparable weed suppression between organic and conventional systems[29].

While precipitation positively affected grain yields across all years and crops, in contrast to hypothesis 5 there was not a significant precipitation by system interaction. This was surprising given the varying levels of soil OMC among systems. Increased OMC is associated with greater soil water-holding capacity; thus, we expected yield to decrease less in systems with greater OMC (OAM and OFG) during years of less than average rainfall[54]. This effect was observed in Pennsylvania where corn and soybean yields increased in organic systems with greater OMC compared with conventional systems during dry years[56]. Despite differences among systems in this study, soil OMC was relatively high in all systems (>3.3%), which may explain the lack of precipitation by system interaction effect on yield. Therefore, it is unlikely that dry weather conditions negatively affected one system more than the others.

Conclusions

The results of this study indicate that yields of corn, sorghum and soybean were greatest in conventional cropping systems, but wheat yields were greatest in an animal manure-based organic cropping system. As expected, the application of animal manure in an organic cropping system increased soil OMC, pH, P, Ca, K, Mg and Zn. However, the potential yield benefits associated with these increases were often negated by intense weed pressure in the organic system. Despite the increase in OMC due to manure application, it may be necessary to include perennial forage, such as alfalfa, in organic crop rotations to prevent losses of soil carbon due to the extensive tillage that is common practice in organic annual-cropping systems. In addition to the improved soil properties associated with alfalfa, this forage crop also provides competitive crop yields in organic compared with conventional systems (when compared with the 12-year county average for conventional alfalfa yield). Future studies should be focused toward a greater understanding of the mechanistic responses of soil biological and physical properties associated with long-term organic management. Moreover, the economics, energy efficiency and greenhouse gas emissions associated with long-term organic management represent areas of increasing interest and potential research opportunity.

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