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Comparing agroecosystems: Effects of cropping and tillage patterns on soil, water, energy use and productivity

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Abstract

We compared soil characteristics, runoff water quantity and nutrient fluxes, energy use and productivity of three farm types in an unusually dry farming season: conventional (continuous corn and deep tillage), rotation (5-year corn–soybean–oats/alfalfa–alfalfa–alfalfa rotation with tillage 2/5 years) and no-till (corn–soybean with no cultivation). Soil organic matter content was highest on the rotation farm, followed by the no-till farm, and lowest on the conventional farm. Nitrate content of the soil did not differ significantly among the three farms, although the conventional farm had a much higher input of fertilizer nitrogen. Soil penetrometer resistance was lower and percent soil moisture was higher in the no-till and rotation systems compared to the conventional farm. Soil macroinvertebrate abundance and diversity were highest on the no-till farm, followed by the rotation farm. No invertebrates were found in the soil of the conventional farm. The conventional farm had the highest runoff volume per cm rain and higher nitrogen (N) loss in runoff when compared to the rotation and no-till farms, as well as a higher phosphorus (P) flux in comparison to the no-till farm. These results indicate that perennial close-seeded crops (such as alfalfa) used in crop rotations, as well as plant residue left on the surface of no-till fields, can enhance soil organic content and decrease runoff. The lower soil penetrometer resistance and higher soil moisture on the rotation and no-till farms show that conservation tillage can increase soil aggregation and water infiltration, both of which prevent erosion. Furthermore, crop rotation, and particularly no-till, promote diverse invertebrate populations, which play an important role in maintaining nutrient cycling and soil structure. Crop rotation and no-till agriculture are less fossil-fuel intensive than conventional agriculture, due to decreased use of fertilizers, pesticides and fuel. In this unusually dry year they provided superior corn and soybean yields, most likely due to higher soil moisture as a result of greater water infiltration and retention associated with cover crops (rotation farm) and crop residue (no-till farm).

Key words: sustainable agriculture, crop rotation, no-till agriculture, soil organic matter, soil compaction, soil invertebrates, agricultural runoff, fossil fuel consumption, corn–soybean productivity

Introduction

In recent years there has been growing concern from farmers, scientists, economists, sociologists, and religious leaders regarding the sustainability of current agricultural practices in the United States[1–2]. Monoculture row cropping, deep tillage and application of high levels of fertilizers and pesticides can result in widespread damage to land and water resources. Conventional agriculture in the US also depends heavily on fossil fuel energy, thus contributing to rising CO_2 levels and global climate change. In order to address the problems of conventional agriculture, some farmers are seeking more sustainable methods of agriculture, including crop rotation, no-tillage and integrated pest management.

Legume-based crop rotations, no-tillage agriculture and reduction of pesticide application can have positive effects on soil, water, energy use and productivity in agroecosystems. While monoculture row cropping tends to deplete soil organic material and nitrogen, crop rotations (particularly those including perennial legumes) tend to restore these essential materials to the land[3–8]. Crop residue left on the surface of no-till fields provides organic matter that enhances soil aggregation and water-retaining capacities, both of which reduce runoff and pollution of aquatic systems[9]. Reduced tillage has also been shown to increase populations of soil macroinvertebrates, which contribute to decomposition and nutrient cycling, a porous soil structure and natural pest control[10–14]. With regards to economic

Table 1. Cultural practices on the study farms.

	Cropping history					
Study farm	**2003**	**2002**	**2001**	**2000**	**1999**	**Tillage**
Conventional corn (CC)	C	C	C	C	C	Moldboard plow
Conventional soybeans (CS)	S	C	C	S	C	Chisel plow/disk ripper
Rotation corn (RC)	S	C	A	A	A	Mulch till (only before C and S)
Rotation soybeans (RS)	S	C	A	A	A	Mulch till (only before C and S)
Rotation alfalfa (RA)	A	A	S	C	A	Mulch till (only before C and S)
No-till corn (NTC)	C	S	C	S	C	No tillage
No-till soybeans (NTS)	S	C	S	C	S	No tillage

C, corn; S, soybeans; O, oats; A, alfalfa.

Table 2. Comparison of 2002, 2003 and 1971–2000 average precipitation levels by month, growing season totals (June–October) and year totals (January–December) at the Faribault, Minnesota weather station (♯212721)[16,17].

	2002 Precipitation (cm)	**2003 Precipitation (cm)**	**1971–2000 Average precipitation (cm)**
January	1.63	0.89	2.67
February	1.40	2.01	1.83
March	5.82	4.50	4.90
April	8.38	5.56	7.14
May	4.70	12.04	9.50
June	26.09	10.77	10.64
July	10.77	6.15	10.90
August	14.55	4.19	11.28
September	7.42	3.96	8.13
October	10.19	2.01	5.66
November	0.33	2.95	5.13
December	1.30	2.97	2.59
Growing season (June–October)	69.01	27.08	46.61
Year total (January–December)	92.56	57.99	80.37

concerns, studies show that conservation practices such as no-till agriculture can increase productivity and decrease costs[15].

The purpose of our study was to evaluate the effects of crop management practices on soil quality and sustainability of agroecosystems in south-central Minnesota. This was accomplished by comparing soil characteristics, water quantity and nutrient fluxes in runoff, energy use and productivity in conventional, crop rotation and no-till farms. Since the 2003 growing season was unusually dry, this study also provides insight into the performance of these farming systems under extreme conditions.

Materials and Methods

In order to assess the effects of crop rotation and no-tillage agriculture, we sampled soil and macroinvertebrate populations from three farm types (conventional, rotation and no-till) with different cropping and tillage methods near Northfield, Minnesota, USA (Table 1). The farms sampled are within 3.5 km of each other, just north or west of the St. Olaf College campus. The farm soils are classified mainly as Lester loams with 2–6% slopes[16]. The conventional corn (CC) field was continuously cropped with corn and tilled with a moldboard plow. The conventional soybean (CS) field was in a corn–corn–soybean (C–C–S) rotation and cultivated with a chisel plow and disk ripper each year. Rotation fields were in a perennial-legume-based, 5-year crop rotation of corn–soybeans–oats/alfalfa–alfalfa–alfalfa (C–S–O/A–A–A). Fields were mulch-tilled before planting of corn and soybeans, but were not tilled during the 3 years that alfalfa was grown. Manure had been applied before planting of corn on the rotation farm over the past 10 years. The no-till farm used a corn–soybean (C–S) rotation and a seed drill to plant directly into the soil through the residue of the previous year's crop, which was left undisturbed following harvest. In 2003, this farm had been under no-till management for 12 years.

Precipitation levels before and during our study in the fall of 2003 were unusually low (Table 2). From January through December of 2003, the Faribault, Minnesota weather station (approximately 18 km south of Northfield) received 57.99 cm of precipitation[17], as compared with a 1971–2000 average of 80.37 cm[17]. During the 2003 growing season (June through October), the Faribault weather station received only 27.08 cm of precipitation[17], as compared with a 1971–2000 average of 46.61 cm[18].

Soil resources

In order to assess soil organic matter, soil nitrates, compaction and moisture, soil samples were collected on 3 days from early September through early October, in 2002 and 2003. In 2002, soil samples were taken from conventional corn (CC), rotation corn (RC) and no-till corn (NTC) fields. In 2003, soil samples were taken from conventional corn (CC), conventional soybean (CS), rotation soybean (RS), rotation alfalfa (RA), no-till corn (NTC) and no-till soybean (NTS) fields. The data presented are from the more extensive 2003 study, with 2002 trends noted in the text.

At each visit to the study sites, we combined five soil cores, 25 cm deep and 2 cm in diameter, from randomly chosen areas for tests of soil organic matter and nitrates, for a total of six samples per farm type. We determined percent organic matter in the soil by finding the ash-free dry weight of a soil subsample, oxidized in a muffle furnace at 500°C for 2 h. Percentage soil organic matter (% SOM) by weight was determined using the formula:

$$\%\text{SOM} = [(W_{\text{ad}} - W_{\text{af}})/W_{\text{ad}}] \times 100\%$$

where W_{ad} = air-dry weight of soil sample and W_{af} = ash-free weight of soil sample. Nitrate analysis was performed by spectrophotometry as described by Hach Company[19].

In order to compare the soil moisture, we took two randomly selected 25 cm deep soil cores on each visit for a total of 6 per field and 12 per farm type. Soil cores were placed in pre-weighed metal tins and re-weighed in the lab to determine fresh weight, then oven-dried at 105°C for 48 h and weighed again to obtain dry weight. Percent soil moisture by weight (θ_{w}) was calculated by:

$$\theta_{\text{w}} = [(W_{\text{f}} - W_{\text{od}})/W_{\text{od}}] \times 100$$

where W_{f} = fresh weight of soil sample and W_{od} = oven dry weight of soil sample.

Soil compaction was determined for each field in 2003 using a Dickey–John penetrometer. Sixteen randomly selected sites were measured in each farm type (eight sites per field). Soil compaction readings were taken at depths of 15 cm and 30 cm.

The exceptional dryness of the 2003 growing season (Table 2) precluded an accurate sampling of invertebrate populations in the top 20 cm of soil, so data from 2002 are presented. Data were collected from conventional corn (CC), rotation corn (RC) and no-till corn (NTC) fields. We examined two randomly chosen plots per farm on 3 days for a total of six samples per field. We used a 25 × 25 cm quadrat frame and excavated to a depth of 20 cm, then searched the soil by hand for macroinvertebrates and recorded the number and classification of each invertebrate in each plot[20]. Insects and other arthropods were classified to order and class, respectively, and earthworms were classified into epigeic, endogeic and anecic functional groups[21]. These functional groups actually reveal more about an organism's response to environmental change than taxonomic groups, as members of particular functional groups tend to dwell in the same soil layer and utilize similar food sources[22]. Data from all six quadrats on each farm were pooled and used to calculate the Simpson (D) and Shannon (H) diversity indexes, respectively, using the following formulas[23]:

$$\text{D} = 1 - \Sigma p_{\text{i}}^2$$

$$\text{H} = -\Sigma p_{\text{i}}(\ln\ p_{\text{i}})$$

where p_{i} = proportion of individuals of a given species.

Water resources

In order to assess the effects of different farming practices on runoff water quantity, we installed a catch-basin in each field to capture runoff (Fig. 1). After two rainstorm events, we collected the water in the buckets of each catch-basin and measured the volume of water collected in a graduated cylinder. We then centrifuged the samples at 5000 rpm for 5 min to remove sediment, decanted the liquid into a separate container, and filtered the water samples through a glass fiber filter. Concentrations of inorganic nitrogen (N) and orthophosphates (P) were determined using the methods described by Sechtig[24] and Liao[25], respectively. N and P concentrations in runoff were converted to fluxes (mg N cm^{-1} rain and μg P cm^{-1} rain) by multiplying concentrations by the volume of runoff water obtained.

Energy use and productivity

In order to compare energy use on the farms, we collected data from each farmer on per-acre application of fertilizer, herbicide and insecticide, as well as fuel required to operate farm machinery for each crop grown. The Handbook of Energy Utilization in Agriculture[26] was used to find percent active ingredient in agricultural chemicals, and the reference Food and Energy Resources[27] was used to convert kilograms of agricultural chemicals and gallons of fuel used into kcal $\text{ha}^{-1}\,\text{yr}^{-1}$. For each farm type (conventional, rotation and no-till) we estimated average yearly fossil fuel energy use. Data on crop yields in bushels acre^{-1} (or bales acre^{-1}) were collected from each farmer at the end of harvest season and converted to kg ha^{-1} (or bales ha^{-1}). Conversions of bushels ha^{-1} to kg ha^{-1} assumed standard bushel weights: corn, 56.00 lbs bushel^{-1} (15.5% moisture); soybeans, 60.00 lbs bushel^{-1} (13.00% moisture); oats, 32.00 lbs bushel^{-1} (14.00% moisture).

Data analysis

We determined mean % SOM, soil nitrate concentration, soil compaction, soil bulk density, soil moisture, invertebrate abundance, water runoff cm^{-1} rain, and fluxes of

Figure 1. A catch-basin constructed to assess the effects of agriculture (rotation soybean field) on soil runoff. Catch-basins consisted of a bucket, 9 in. (23 cm) in diameter, placed into a hole dug in the ground, beneath a raised plywood shelter. The shelter ensured that no rainwater would enter the bucket directly, and therefore that all water collected represented surface runoff from the fields. Pieces of plywood, 4 ft (1.2 m) long, were placed to form a 90° angle with the bucket at its vertex. This standardized the width of the collecting area to approximately 5.7 ft (1.7 m).

N and P in runoff for the three categories of farms. Because our data sets did not exhibit equal variances, we compared means using the nonparametric Kruskal–Wallis test using StatView 5.0 software[28].

Two-sample *t*-tests were used to compare the Simpson and Shannon diversity indexes between fields[23]. It was not possible to calculate a diversity index for the conventional farm because no invertebrates were found there.

Results and Discussion

Soil resources

Soil organic matter (SOM) was highest on the rotation farm, followed by the no-till farm, with the lowest soil organic matter levels on the conventional farm ($P = 0.0034$; Fig. 2).

These findings are consistent with studies on nutrient cycling in agroecosystems demonstrating a loss of soil organic matter in conventionally cropped and tilled soils[4,9] and an increase in SOM in cropping systems incorporating perennial legumes[5]. On the farm practicing a 5-year crop rotation, the high SOM content may be attributed to decreased erosion due to the presence of soil-conserving alfalfa crops during 3 out of every 5 years, as well as plant residues left by perennial legumes[7,29]. Decreased erosion due to protection of soil surface by plant residues may have also contributed to the relatively high levels of SOM on the no-till farm. Slower processes of biological oxidation on the no-till farm[4,8,11] and stimulation of fungal growth, which have a high efficiency of carbon assimilation[9] may also help account for the higher levels of SOM on the no-till farm compared to the conventional farm.

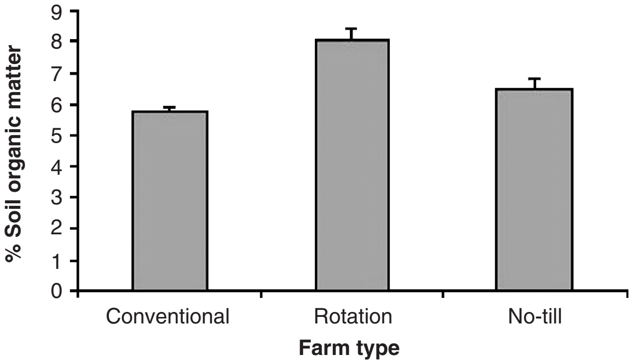

Figure 2. Percent soil organic matter by weight in conventional, rotation and no-till agroecosystems. Organic matter was calculated from soil cores 25 cm deep. Means ± standard error are shown. ($N = 6$, $P = 0.0034$).

Our 2003 data, showing the highest SOM levels on the rotation farm, followed by the no-till farm, with the lowest SOM levels on the conventional farm, corroborated our initial findings from 2002. In 2002, we found soil organic matter levels of $3.97 \pm 0.05\%$ on the conventional farm, $7.81 \pm 0.75\%$ on the rotation farm, and $5.86 \pm 0.17\%$ on the no-till farm ($P = 0.003$). Organic matter levels on each farm remained fairly consistent from 2002 to 2003. The apparent increase in SOM for the conventional farm from 2002 to 2003 may be due to the fact that in 2002, we sampled only fields tilled with a moldboard plow (the most intensive form of tillage), while in 2003 we included fields tilled with a disk ripper (a less intensive form of tillage) in the conventional category.

It should be noted that if soil organic matter was calculated on a volume basis rather than a weight basis, the differences between the conventional farm and the rotation and no-till farms might be somewhat reduced, owing to the greater compaction, and therefore greater bulk density, of soil on the conventional farm (see below). However, the relatively higher percent soil organic matter by volume on the conventional farm in 2003 may not necessarily have a positive impact on crop growth, as it has been shown that root growth decreases as compaction (penetration resistance) increases[30]. With a smaller root surface area in contact with the soil, crops grown in compacted soil may be less able to take up nutrients released as organic matter decomposes.

Soil nitrates did not show significant differences between farms in 2002 ($P = 0.243$) or 2003 ($P = 0.8539$). However, other experiments have indicated the beneficial effects of perennial legumes and no-till agriculture on soil nitrogen. Because legume crops possess symbiotic (mutualistic) nitrogen-fixing bacteria in their root nodules, crop rotation incorporating perennial legumes has been shown to contribute to higher soil nitrogen levels[5,7,11,29]. No-till farms are also likely to retain more soil nitrogen than conventionally tilled farms, due to decreased erosion and loss of small organic particles to which nitrogen is bound[4,31].

There are several possible reasons why we did not observe higher nitrogen levels on the rotation and no-till farms in comparison to the conventional farm. First, nitrate levels were highly variable. The small sample size used may not have been representative of the actual levels of soil nitrogen or large enough to resolve differences between farms. The second possible explanation lies in the nitrogen fraction tested. We only tested soil for nitrate, an inorganic ion (NO_3^-). However, much of the nitrogen in the legumes of the rotation and no-till farms (soybeans and alfalfa) is contained in ammonia or organic forms. Total soil nitrogen levels may have been much higher than the nitrate levels indicate on the rotation farm in particular (with soybeans + 3 years of alfalfa), but also on the no-till farm (with soybeans every other year). Indeed, a study by Drinkwater et al.[5], which showed increased nitrogen levels in crop rotations with perennial legumes, considered nitrogen stored in above- and below-ground biomass (litter and roots).

Higher nitrogen fertilizer application on the conventional farm may also account for the fact that soil nitrogen levels were not significantly lower than the rotation and no-till farms. (Average N applications for each farm in 2003, including NH_3-N and NPK-N, were: 187.3 kg ha^{-1} on the conventional C–C–C farm, 124.9 kg ha^{-1} on the conventional C–C–S farm, 49.2 kg ha^{-1} on the rotation farm, and 67.5 kg ha^{-1} on the no-till farm.) However, studies have shown that inorganic nitrogen fertilizers cannot substitute for biologically fixed nitrogen added directly to the soil via legumes. Inorganic nitrogen is likely to be leached during the fallow period, or lost to soil erosion or denitrification, rather than retained in the soil[5,29]. Thus, high levels of soil nitrogen observed on the conventional farm may not persist.

Soil compaction at both 15 and 30 cm depths (Fig. 3) was lowest on the no-till farm, followed by the rotation farm. The conventional farm had the most compacted soil. Lower levels of soil disturbance, less use of heavy machinery[32], and higher levels of organic matter[7,33] may have promoted greater soil aggregation on the no-till and rotation farms compared to the conventional farm. Since aggregates help maintain pores of various sizes, one would expect the organic-matter-rich soil from these farms to be more porous and less compacted than soil from the deep-tillage conventional farm[34].

Evidence regarding the effects of decreased tillage on soil structure is somewhat contradictory. While some studies have observed an increase in bulk density in fields converted to no-till (the opposite of the trend toward decreased compaction that we observed), our findings are consistent with other studies that found a decrease in bulk density of no-till fields, particularly when organic matter content of the soil increased[30,33]. The no-till fields in our study may have exhibited less soil compaction than the conventional fields because the no-till fields we sampled have been under no-till management for more than 10 years. In contrast, a study showing greater bulk density in no-till fields[30] sampled from fields converted from conventional tillage to no-till within the past 5 years. There is often a temporary increase in soil bulk density and compaction following conversion from conventional tillage to no-till, until the soil recovers its natural structure and builds up organic matter, which increases soil porosity and decreases bulk density and compaction[30,33]. Therefore, our findings of decreased compaction in fields under no-till management for more than 10 years may not be in conflict with studies showing greater soil bulk density in no-till fields, if these studies were conducted early in the field's conversion to no-till.

Soil moisture levels were significantly higher in the rotation and no-till farms in comparison with the conventional farm (Fig. 4). These findings are consistent with a study by Holland and Coleman[9], which showed that leaving crop residue on the soil surface significantly decreased evaporation rates and resulted in moister soils than those of farms in which crop residue had been plowed under. Crop rotation and no-till agriculture may also increase soil moisture by increasing soil porosity and infiltration[1], while erosion due to conventional tillage practices can decrease infiltration by up to 93%[14]. In addition, no-till and reduced-till farming methods, such as those practiced on the rotation fields, may also have contributed to enhanced soil structure

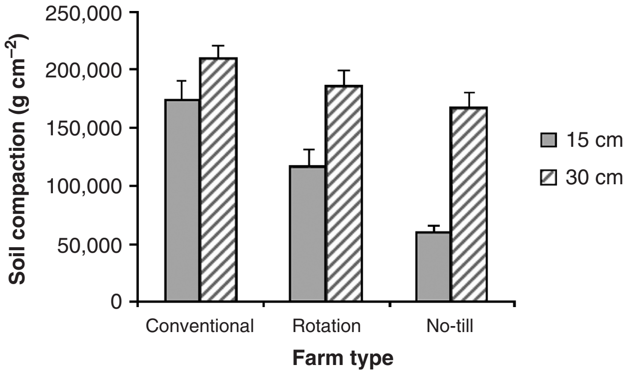

Figure 3. Soil compaction at 15 cm ($N = 16$, $P < 0.0001$) and 30 cm ($N = 16$, $P = 0.0520$).

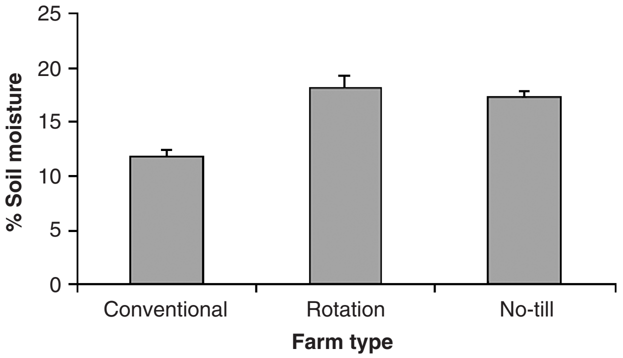

Figure 4. Percent soil moisture by weight in conventional, rotation and no-till agroecosystems. Percent soil moisture was calculated from soil cores 25 cm deep. Means ± standard error are shown. ($N = 12$, $P = 0.0002$).

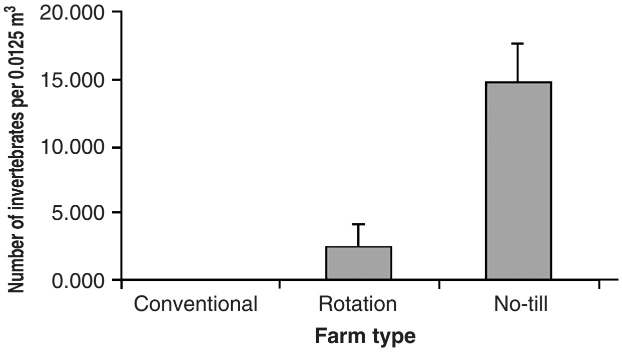

Figure 5. Soil invertebrate abundance in conventional, rotation and no-till agroecosystems. Invertebrate abundance is reported as average number of invertebrates found in a soil sample with a volume of $0.0125\,m^3$ (25 cm long × 25 cm wide × 20 cm deep). Means ± standard error are shown ($N = 6$, $P = 0.002$).

by supporting a greater abundance and diversity of soil invertebrates. This hypothesis is supported by our data on macroinvertebrates in the three farm fields (see below). Macroinvertebrate activities, such as burrowing, enhance formation of stable aggregates and increase porosity and water infiltration.

Although all the farm fields had lower moisture levels in 2003 than in 2002, due to the 2003 drought, we found similar trends in soil moisture in our 2002 study. The rotation farm had the highest soil moisture content, with 32.9 ± 3.2%, followed by the no-till farm with 24.0 ± 0.3%, and the conventional farm had the lowest soil moisture with 19.7 ± 1.2% ($P < 0.001$).

Soil invertebrates were most abundant on the no-till farm, followed by the rotation farm. No soil invertebrates were found in the soil of the conventional farm (Fig. 5). With regards to diversity, three functional groups of earthworms, five orders of insects, and three classes of other arthropods were found in the soil of the no-till farm. The three functional groups of earthworms were also observed on the rotation farm, but we found only one insect order (Coleoptera) and one other class of arthropods (Diplopoda). The Simpson (D) and Shannon (H) diversity indexes were higher for the no-till farm (D = 1.33; H = 2.04) than the rotation farm (D = 0.45; H = 0.83), and lowest (D = 0.00; H = 0.00) for the conventional farm. Our results are consistent with other studies documenting the greater invertebrate abundance and diversity in no-till farms when compared with conventional farms[10,14,20,33,35].

Soil disturbance, soil compaction and alteration of habitat due to use of the moldboard plow have been shown to decrease the biomass and diversity of soil invertebrate populations[10–14,20,33,35–41]. These factors could all play a role in the absence of invertebrate populations on the conventional farm, as the invertebrate-rich decomposition biotrope, dependent on the presence of plant litter on soil, is nearly eliminated in conventionally tilled fields[33]. Furthermore, tillage destroys the stratified surface soil horizons that provide a diversity of habitat niches in undisturbed soils. Excessive use of crop protection chemicals may also prove toxic to invertebrate populations, thus decreasing abundance and diversity[11,12,14,20]. Application of chemical pesticides, which was highest on the conventional farm, could have played a role in the lack of macroinvertebrates observed. These findings are supported by a previous study on St. Olaf farmland[42].

In contrast to conventional systems, no-till or minimum-till systems increase earthworm abundance, because the crop residue left on the soil surface promotes fungi-based food webs[36,40], protects earthworms from desiccation and predation[33] and provides a more stable microclimate at the soil surface[3,33]. Inclusion of legumes or fibrous root crops in rotation may also stimulate larger populations of soil invertebrates by increasing below-ground carbon and nitrogen inputs to the soil[10]. In our study, tillage practices appear to account for the differences in invertebrate abundance and diversity, as the no-till farm had the highest and most diverse invertebrate populations. Thus, monocrop farming and deep tillage (as on the conventional farm sampled) decrease the diversity of food sources and invertebrate habitats present in a natural system, resulting in less invertebrate abundance and diversity, while crop rotations and no-tillage agriculture preserve habitat and invertebrate diversity[13,41].

Water resources

Runoff volume per cm rain was highest on the conventional fields, averaging 35 times that of the no-till fields and 60 times that of the rotation fields (Table 3). Our results, indicating higher runoff in exclusively row-cropped, conventionally tilled agricultural fields, are consistent with those of other investigators. Other studies have shown that no-till systems[33] and less intensive tillage[43] systems also reduce runoff volume.

Table 3. Water resources data for conventional, rotation and no-till agroecosystems found in $0.0125\,m^3$ soil samples. Means ± standard error are shown.

	Sample no. per farm	Conventional	Rotation	No-till	*P* value
Runoff volume ($ml\,cm^{-1}$ rain)	4	684.6 ± 631.3	11.7 ± 9.6	19.5 ± 11.6	0.0244
N flux in runoff ($mg\,N\,cm^{-1}$ rain)	4	0.3 ± 0.3	0.0 ± 0.0	0.0 ± 0.0	0.2621
P flux in runoff ($\mu g\,P\,cm^{-1}$ rain)	4	14.0 ± 12.0	44.2 ± 37.8	2.9 ± 2.1	0.7718

Several factors may have contributed to reduced water losses from the rotation and no-till systems in our study. As discussed previously, increased ground cover and root area (from perennials on the rotation farm and crop residues left on the surface of no-till fields) increase infiltration of rainwater, thus decreasing runoff[3,33]. More porous, less compacted soil structures on the rotation and no-till farms may also play a role in reducing runoff volume.

The conventional farm also had higher N loss in runoff when compared to the rotation and no-till farms, as well as a higher P flux in comparison to the no-till farm (Table 3). Although these differences were not statistically significant, this is probably due to the very limited sample size (two samples per field), owing to lack of rainstorm events during the study. The lower N fluxes in runoff from rotation and no-till farms, and lower P fluxes from the no-till farm, in comparison to the conventional farm, are consistent with other studies on transport of nutrients in agricultural systems. For example, elevated NO_3^- concentrations have been observed in runoff from corn monocultures[44]. Other studies have also shown that no-tillage agriculture can reduce sediment and associated phosphorus losses to aquatic systems[43,45,46].

Our observation that the conventional farm exhibited higher N fluxes in runoff than the rotation and no-till farms was probably due to high fertilizer use combined with high leaching due to shallow rooting systems on the conventional farm. In comparison to biologically fixed nitrogen, plants tend to use such fertilizer nitrogen inefficiently, leaving excess nitrate ions to be leached into the watershed as nutrient pollution[29,47]. On the other hand, rotation of corn with soybeans and alfalfa decreases the amount of fertilizer that must be applied to obtain good yields. Lower fertilizer use may explain the lower N fluxes observed in runoff from the rotation fields, as no fertilizer was applied during the years in which soybeans and alfalfa were grown (4 out of every 5 years).

Lower nutrient fluxes of N and P in runoff from the no-till fields in comparison to the conventional fields may be attributed to the fact that no-till farming prevents erosion by providing physical protection from wind and rain, and by increasing water infiltration rates (as discussed previously). Given that about 75–90% of P exported from cultivated lands is adsorbed to soil particles eroded in runoff, decreased erosion on the no-till farm due to plant residues on the soil surface could substantially reduce P loss[48].

The elevated P loss from the rotation agroecosystem as compared to the conventional system is somewhat perplexing. The high P loss from the rotation system is entirely attributable to P loss from the alfalfa fields, as the rotation soybean fields had no runoff during either rainstorm event. Given the high proportion of ground cover and therefore the presumably low soil erosion rates in the alfalfa fields, one would expect lower loss of P in surface runoff. The high levels of P in runoff from the rotation alfalfa fields may be the result of manure application or P accumulation in crop residues near the soil surface, where it can be transported to runoff[45]. Further research is needed to determine if P loss is actually higher on the alfalfa fields in comparison to other fields, and to elucidate the mechanism for P loss in such a low-erosion, cover-crop environment.

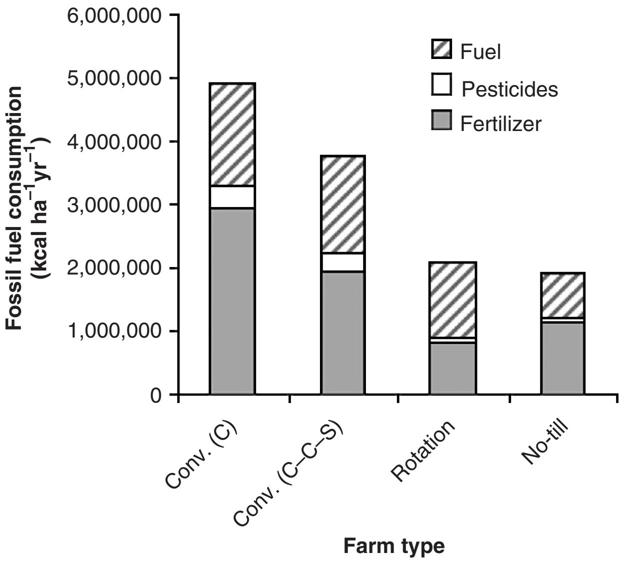

Figure 6. Fossil fuel energy consumption (kcal ha^{-1} yr^{-1}) in conventional (C–C–S), rotation (C–S–O/A–A–A) and no-till (C–S) agroecosystems during the 2003 growing season.

Energy use and productivity

Fossil fuel consumption was highest on the conventional farms, followed by the rotation and no-till farms (Fig. 6). The conventional farm had the highest energy consumption for fertilizer, pesticides and fuel when compared with the rotation and no-till farms.

On the rotation and no-till farms, crop rotation and decreased rates of soil erosion may have reduced the need for fertilizer and pesticide consumption, thus decreasing energy use. Perennial legumes such as alfalfa are capable of contributing over 200 kg of N ha^{-1} to the soil, which is sufficient to meet the nitrogen requirements of most subsequent grain and cover crops[3,49]. The low erosion rates associated with crop rotation and no-tillage agriculture can also greatly reduce nutrient losses from these systems, obviating the need for high inputs of inorganic nutrient application. Crop rotation also enhances pest control by breaking pest life cycles, thus decreasing the amount of chemical pesticides that must be applied. For example, rotating corn and soybeans eliminates the need for insecticides to control rootworm pests[50]. This can be seen in that the most diversified farm—the rotation C–S–O/A–A–A—had the lowest energy consumption due to pesticide use.

No-till agriculture greatly reduced the energy consumption associated with machinery and fuel use by eliminating plowing: the average total fuel use of no-till agriculture was less than half that of conventional agriculture. A study by West and Marland[51], which calculated C emissions due to machinery energy consumption (averaged over corn, soybean and wheat), found even greater differences between conventional and no-till fields. While conventional tillage resulted in emissions of 69.0 kg C ha^{-1} yr^{-1}, no-till fields were responsible for 23.3 kg C ha^{-1} yr^{-1}.

Although not as low as fuel use on the no-till farm, the rotation farm also had lower fuel use than the conventional farm, mainly due to reduction in the intensity and frequency of plowing (fields are tilled only before planting of corn and soybeans and are left unplowed during the 3 years that alfalfa is grown). However, the rotation farm used fuel for cutting, raking and baling of alfalfa that was not needed in either the conventional or the no-till system.

Our calculations indicate that rotation and no-till systems use substantially less fossil fuel in comparison to conventional systems. This alone indicates that crop rotation and no-till agriculture could play an important role in mitigating global climate change, were they adopted on a large scale. However, the benefits of crop rotation and no-till in reducing radiative forcing of the atmosphere include not only decreased fossil fuel emissions, but also increased carbon storage in soil organic matter. A study of the global warming potential (GWP) of different agricultural systems[52] found that carbon accumulated at a rate of 44.0 g C m^{-2} yr^{-1} in a perennial alfalfa field and 30.0 g C m^{-2} yr^{-1} in a no-till field, while a conventionally tilled field accumulated no carbon. The net GWP for the alfalfa field was actually negative (-20 g CO$_2$ equivalents m^{-2} yr^{-1}), and that of the no-till field was less than one-eighth that of the conventional field (14 compared to 114 g CO$_2$ equivalents m^{-2} yr^{-1}).

Per-hectare production of corn and soybean crops was greater on the rotation and no-till farms than on the conventional farms (Table 4). This concurs with a 1996 study comparing the conventional and rotation farms. Although the no-till system was not included in this study, per-hectare production of corn and soybean crops was greater on the rotation farm than on the conventional farm[42].

A number of factors associated with soil fertility may have contributed to increased yields on the rotation and no-till farms in our study. First, the higher levels of organic matter on the rotation and no-till farms may have increased their yields relative to the conventional farm. The majority of available nutrients needed for crop growth are contained in organic matter: 95% of available nitrogen and 25–50% of available phosphorous in the soil are contained in organic matter[11,14]. Improved soil structure and decreased erosion rates may also have contributed to superior yields on the rotation and no-till farms. Topsoil losses associated with monoculture row cropping and deep tillage (as on the conventional farm) can significantly decrease soil fertility, water infiltration and holding capacity, and beneficial soil biota, thus reducing crop yields[14]. Due to the lack of growing season precipitation in the 2003 growing season, increased water infiltration and retention associated with cover crops (on the rotation farm) and crop residue (on the no-till farm) could have been a major factor in increasing the yields of the rotation and no-till farms in comparison to the conventional farm. Finally, increased invertebrate activity on the rotation and no-till fields could have increased soil fertility and soil moisture, and therefore productivity. This hypothesis is supported by an experiment comparing farm fields before and after the introduction of earthworms, which found a 28% increase in production and a 100% increase in water infiltration 10 years after introduction[53]. Crop diversity on the rotation farm may also have increased productivity by preventing crop losses due to pest and disease outbreaks[54].

Summary and Conclusions

Design of sustainable agroecosystems necessitates that we understand the effects of farming practices on the long-term sustainability of soil and water resources. Nutrient content, resistance to erosion and soil invertebrates are all important aspects of an agroecosystem that must be considered in plans for maintaining the fertility and productivity of the soil. This study indicated that crop rotation and reduced tillage have a number of positive effects on the ecological sustainability of agroecosystems.

Soil organic matter was highest on the rotation farm, followed by the no-till farm, and lowest on the conventional farm. The crop diversity and plant residue left on the soils of these fields, as well as the continuous ground cover provided by alfalfa in the rotation fields, prevented erosion and increased soil organic content, which is critical for crop growth. Our study also indicated that no-tillage and minimum-till agriculture have positive effects on soil structure. Soil compaction was lower and percent soil moisture was higher in the no-till and rotation fields compared to the conventional fields. Less use of soil-compacting heavy machinery and greater retention of organic matter in these soils promoted aggregate formation, maintained porosity and increased water infiltration, all of which served to enhance the physical structure of the soil and decrease

Table 4. Productivity of conventional, rotation and no-till agroecosystems for the 2003 growing season.

Crop	Conv. (C)	Conv. (C–S)	Rotation (C–S–O/A–A–A)	No-till (C–S)
Corn: kg ha^{-1} (bushel acre^{-1})	7407 (118)	7407 (118)	9416 (150)	8286 (132)
Soybeans: kg ha^{-1} (bushel acre^{-1})	–	1345 (20)	2556 (38)	2421 (36)
Oats, seeds: kg ha^{-1} (bushel acre^{-1})	–	–	3228 (90)	–
Oats, straw: bales ha^{-1} (bales acre^{-1})	–	–	148 (60)	–
Alfalfa: bales ha^{-1} (bales acre^{-1})	–	–	370 (150)	–

susceptibility to erosion. No-till and minimum-till methods of cultivation were also less disruptive of soil invertebrates, which helped maintain fertility and physical structure of the soil. Indeed, we found that invertebrate diversity and abundance was highest on the no-till farm and lower on the reduced-tillage rotation farm, while the soil tilled with a moldboard plow on the conventional farm supported no invertebrates.

Water quality is another concern that must be taken into account in order to reduce the environmental impacts of agriculture, which often contributes to eutrophication and pollution of aquatic ecosystems. We found that the rotation farm had the lowest runoff levels, followed by the no-till farm. The conventional farm had the highest volume of runoff and the highest N loss in runoff. Lower fertilizer application and increased ground cover due to perennial crops and crop residues on the rotation and no-till fields may have played a role in increasing infiltration of rain-water, thus decreasing runoff.

In light of decreasing fossil fuel energy supplies and the threat of climate change due to increased CO_2 inputs to the atmosphere, reducing fossil fuel use in agriculture should also be a priority. Our study indicated that the crop rotation and no-till farms consumed much less fossil fuel than the conventional farms, due to lower inputs of fertilizers, pesticides and fuel.

Finally, productivity must also be considered when comparing agricultural systems, as a farm must be economically, as well as ecologically, sustainable. Our study and other research demonstrating the positive effects of perennial legume-based crop rotations and no-tillage agriculture on agroecosystem productivity[3–8] indicated that adoption of practices such as those on the rotation and no-till farms sampled could have both environmental and economic benefits. Such research must be integrated with the political, social and philosophical aspects of agricultural activity in order to ensure sustainability of human food resources and rural communities.

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