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Impact of reduced tillage on soil organic carbon and nutrient budgets under organic farming

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Abstract

No-tillage (NT) and reduced tillage (RT) systems are well-known management tools for reducing soil erosion and improving soil fertility. NT and RT may improve the environmental and economic performance of organic farming, but they are still not common practice among organic farmers. This paper presents the effects of tillage [RT versus conventional tillage (CT)], fertilization (slurry versus manure compost) and biodynamic preparations (with versus without) on soil fertility indicators such as soil organic carbon (C_{org}), microbial biomass and microbial activity, soil nutrients and nutrient budgets in an organic farming system during the first six-year crop rotation period of a long-term experiment on a clayey soil in a temperate climate. RT caused stratification of soil organic carbon (C_{org}), microbial properties and soil nutrients in the soil profile. Under RT, C_{org} in the 0–10 cm soil layer increased from 2.19 to 2.61% (w/w) from 2002 to 2008, whereas it remained constant under CT. In both tillage treatments, C_{org} remained constant in the 10–20 cm soil depth. Microbial biomass C increased by 37% under RT in the 0–10 cm soil depth and microbial activity [dehydrogenase activity (DHA)] was enhanced by 57%. Soil microbial biomass C and DHA in the 10–20 cm soil depth were also higher under RT (+10 and +17%, respectively). Soluble soil P and K were 72 and 40%, respectively, higher in 0–10 cm soil depth under RT when compared with CT. Fertilization showed no effects on the measured soil properties. Biodynamic preparations increased solely the C_{mic}-to-N_{mic} (soil microbial biomass C to soil microbial biomass N) ratio by 7% in the 0–10 cm soil depth. Nutrient budgets for P were balanced in all treatments, but N and K exports were higher under RT compared to CT. We conclude that RT is a suitable method for increasing indicators of soil fertility in organic farming systems. The combined effects of RT and an organic farming system with a diverse, ley-based crop rotation and organic fertilization merit further promotion and it may be considered for supporting actions by the agricultural policy schemes.

Key words: conservation tillage, soil fertility, organic fertilization, biodynamic preparations, nutrient budget, soluble soil nutrients

Introduction

Soil erosion and other forms of soil degradation are major problems facing agriculture today. Soils are not renewable over a human timescale. Most arable soils are prone to degradation, mainly caused by soil mismanagement. The degradation processes are more dependent on 'how' rather than on 'what' crops are grown[1], highlighting the importance of sustainable soil and crop management.

No-tillage (NT) and reduced tillage (RT) systems are well-known management tools for preventing soil erosion and conserving soil fertility[2]. A positive effect on soil organic carbon (C_{org}) contents in the superficial soil layer has frequently been reported[2–7], whereas the effects on C_{org} in the whole profile are still a matter of controversy[8]. NT and RT cause a stratification of C_{org} and microbial properties in the soil profile[3,6,9,10]. The intensity of tillage operations in RT and the amount and management of above-ground crop residues affect the degree of stratification. Total N, organic N, mineralizable N, P and K usually follow the same pattern with a concentration in the surface layer and no change or decrease below[10].

Organic farming practices are reported to have a positive impact on air, soil, ground and surface water and biodiversity[11]. Multiple cropping systems, crop rotation, cover crops, organic fertilizers and minimum tillage can add organic matter to the soil and increase its capacity to circulate nutrients, air and water[11]. Crop production in organic farming relies and depends on nutrient transformation processes in the soil[12]. Soil quality is thus an important factor in organic farming and C_{org} is a lynchpin in this system. C_{org} in the topsoil is driven by interacting influences of climate, topography, soil type and aspects of crop management such as fertilization, tillage and crop rotation[10]. Conversion of natural land to crop production and tillage generally leads to a loss of C_{org}[13].

C_{org} was reported to remain constant in an organic farming system including ley-based crop rotations and application of organic fertilizers, while it decreased under conventional farming with mineral fertilization[12]. Munro et al.[14] found organically managed topsoils to contain a higher percentage of organic matter, total N and available P when compared with their conventionally managed counterparts at 14 paired sites in England. Drinkwater et al.[15] argue that the higher quality of added organic matter in organic farming leads to an accumulation of C_{org}. Microbial communities are key regulators of soil organic matter dynamics and nutrient availability[16]. Soil microbial biomass and activity, both indicators of biological soil fertility, are enhanced by organic farming[12,16]. To ensure both short-term productivity and long-term sustainability, achieving a balance between inputs and outputs of nutrients is critical, especially as the use of imported materials to build soil fertility is restricted under organic farming[17]. Suitable crop rotations containing legumes produce surpluses in the N budgets of organic farms. P and K budgets show both surpluses and deficits, depending on the farm type and the import of nutrients[17,18].

The International Federation of Organic Agriculture Movements[19] recommends that organic farmers 'take measures to prevent erosion, compaction, salinisation and other forms of soil degradation'. Loss of topsoil should be minimized 'through minimal tillage, contour ploughing, crop selection, maintenance of soil plant cover and other management practices that conserve soil'.

Although conservation tillage (NT and RT) may improve the environmental and economic performance of organic farming, it is still not very common among organic farmers[10]. There are major concerns about the adoption of conservation tillage. Increased weed pressure under conservation tillage as a result of mechanical weed control techniques not adapted to high levels of crop residues on the surface would appear to be the main problem. Topsoil compaction, especially during the first years of transition and with limited availability of N mainly at the beginning of the growing season, also impedes conversion to conservation tillage. Well-drained clays, stable loams and calcareous soils combined with moderate precipitation are favorable conditions for conservation tillage under organic farming conditions. Suitable crop rotations with a high weed-suppressing capacity include a ley phase, cover crops and intercropping[10].

The incorporation of the ley is a critical point under RT[10,20]. Only a few experiments have investigated RT under organic farming conditions. Severe weed competition[20–22] and technical difficulties while incorporating grass–clover sods[20] led to the conclusion that an occasional use of the moldboard plough is inevitable to overcome weed pressure under RT in organic farming[23]. Schulz et al.[24] consistently found similar yields in CT and RT, when at least shallow turning of the soil was carried out. The stratification of C_{org}, soil nutrients and microbial properties with RT in organic or conventional farming systems all developed in a similar way. Under organic farming, RT changed the allocation of C_{org} within the topsoil but did not enhance C_{org} over the whole investigated soil profile[24]. Emmerling[25] reported an increase in C_{org} in the 0–25 cm soil depth where C_{org} was enhanced in the upper layer (0–15 cm) and decreased in the layer below (15–25 cm). Microbial biomass and microbial activity in these soils were stratified under RT; there was an overall increase in microbial properties but the content of plant-available P in the investigated soil layer did not change[25].

Conservation tillage (NT and RT) in organic farming has not yet been successfully adapted and further research into the adaptation of conservation tillage to different soils and climatic conditions, the development of suitable crop rotations and management practices to promote weed control and new strategies to remove and incorporate leys in a conservation tillage system are required[10]. The influence of different fertilization strategies in organic farming systems with and without livestock on N-mineralization and thus on reduced N supply under conservation tillage is not yet clearly understood.

In the present experiment the implementation of RT in an organic farming system with livestock was studied. Two fertilization strategies, the effects of biodynamic preparations and their interactions with soil tillage were investigated. Results of the conversion period from CT to RT showed an increase in C_{org}, microbial biomass and microbial activity in the superficial soil layer over the first 3 years. In the first experimental period, average yields of cereals and sunflowers under RT were 93% of those obtained under CT[26]. After conversion, yields of fodder crops such as grass–clover and silage maize were 29% higher under RT, despite a considerably higher weed infestation of silage maize under RT[27], directing the focus on soil fertility. This paper presents the effects of tillage, organic fertilization strategies and biodynamic preparations on soil fertility indicators such as C_{org}, microbial biomass, microbial activity, soil nutrients and nutrient budgets after the first 6-year crop rotation period of a long-term experiment on a clayey soil in a temperate climate.

Table 1. Dates of soil tillage in the different tillage systems.

System	Crop	Tillage	Date
Conventional	Winter wheat	Plough	October 11, 2002
		Rototiller	October 30, 2002
	Intercrop—Oat–clover	Rototiller	August 19, 2003
	Sunflower	Plough	February 26, 2004
		Rototiller	April 22, 2004
	Spelt	Plough	November 8, 2004
		Rototiller	November 16, 2004
	Grass–clover	Rototiller	August 13, 2005
	Silage maize	Plough	February 25, 2008
		Rototiller	May 9, 2008
Reduced	Winter wheat	Rototiller	October 30, 2002
		Chisel	August 6, 2003
	Intercrop—oat clover	Rototiller	August 19, 2003
	Sunflower	Rototiller	April 22, 2004
	Spelt	Rototiller	November 16, 2004
	Grass–clover	Rototiller	August 13, 2005
	Catch crop—winter pea	Stubble cleaner	September 14, 2007
		Chisel	September 15, 2007
		Rototiller	October 11, 2007
	Silage maize	Stubble cleaner	May 9, 2008
		Rototiller	May 9, 2008

Table 2. Organic matter (OM) input (manure, slurry and green manure) in the first crop rotation period (2003–2008) ($\mathrm{t\,OM\,ha^{-1}}$).

				Wheat 2003	Sunflower 2004	Spelt 2005	Grass–clover		Silage maize 2008	Total	Average yearly input
							2006	2007			
Treatment											
I	Con	MC	P−	2.82	1.08	2.15	2.36	1.30	0.76	10.47	1.75
II	Con	MC	P+	2.68	1.25	2.05	2.30	1.26	0.76	10.31	1.72
III	Con	Slu	P−	2.07	0.72	0.94	2.31	1.39	0.21	7.63	1.27
IV	Con	Slu	P+	2.07	0.72	0.94	2.19	1.38	0.26	7.55	1.26
V	Red	MC	P−	2.82	1.08	2.43	2.33	1.30	2.49	12.45	2.07
VI	Red	MC	P+	2.68	1.25	2.33	2.28	1.26	2.49	12.29	2.05
VII	Red	Slu	P−	2.07	0.72	1.22	2.38	1.39	1.94	9.71	1.62
VIII	Red	Slu	P+	2.07	0.72	1.22	2.25	1.38	1.98	9.62	1.60

Silage maize 2008, RT including pea green manure; OM, organic matter.
Con, CT; Red, RT; MC, manure compost; Slu, slurry; P−, without preparations; P+, with preparations.

Material and Methods

Field experiment

In autumn 2002, a field experiment was conducted at Frick, Switzerland (47°30′N, 8°01′E) involving factors such as tillage, fertilization and biodynamic preparations. A detailed description of the experiment is given by Berner et al.[26].

CT uses a moldboard plough operating at 15 cm depth. A chisel plough (15 cm) was used in the RT system and grass–clover in the RT system was superficially incorporated with a stubble cleaner running at 5 cm depth. Seedbed preparation was performed by a rotary harrow in both tillage systems (Table 1).

Inputs of organic matter (Table 2) were higher in the manure compost than in the slurry system due to the use of straw for animal bedding. The experimental farm where the experiment is performed operates at a stocking density of 1.8 livestock units (LU) $\mathrm{ha^{-1}}$ consisting mainly of cattle. The farm has 19 ha of grassland and pastures and 13 ha of arable land. Mainly fodder crops are grown and additional fodder for swine breeding is purchased. Fertilization was planned at a stocking density of 1.4 LU $\mathrm{ha^{-1}}$. Differences in fertilization levels of N, P and K were due to different proportions of excreted elements in solid and liquid organic manure types in the stable system and to N losses during manure storage. We aimed at achieving identical fertilization levels for P and thus accepted differences for N and K. Consequently, plots with slurry fertilization received N, P and K at levels of 1.13, 1.41 and 1.17 LU $\mathrm{ha^{-1}}$, respectively. Fertilization with the manure compost treatment was

Table 3. *F*-values and significance levels of the mixed-model with repeated measures in 2002, 2005 and 2008 for pH_{H_2O} and soil organic carbon (C_{org}).

	pH_{H_2O}		C_{org}	
	0–10 cm	**10–20 cm**	**0–10 cm**	**10–20 cm**
Tillage	19.94*	0.69	84.01**	5.35
Fertilization*Preparations	1.61	0.89	1.77	0.7
Tillage*Fertilization*Preparations	1.18	0.58	0.52	1.76
Year	32.54***	17.53**	37.91***	4.67(*)
Year*Tillage	8.33*	0.22	22.82**	0.47
Year*Fertilization*Preparations	2.13(*)	0.36	1.04	0.24
Year*Tillage*Fertilization*Preparations	2.35(*)	1.85	2.24(*)	2.21(*)

(*)$P < 0.1$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

carried out at levels corresponding to 1.18, 1.53 and 1.09 LU ha^{-1} for N, P and K, respectively (see Table 7 for average yearly inputs).

The biodynamic preparations (P) consisted of the following: P 500, cow-manure fermented in a cow horn; P 501, silica stored in a cow horn. These were applied at rates of 250 and 4 g ha^{-1}, respectively and sprayed three times per season on the relevant plots. Composting additives in the biodynamic treatment were yarrow flowers (P 502, *Achillea millefolium* L.), camomile flowers (P 503, *Matricaria recutita*, L.), stinging nettle (P 504, *Urtica dioica*, L.), oak bark (P 505, *Quercus robur*, L.), dandelion flowers (P 506, *Taraxacum officinale*, Wiggers) and valerian flowers (P 507, *Valeriana officinalis*, L.); these were added at the start of manure composting or slurry storage[28,29]. In total, 10 g preparations were added to about 2 t of composted raw material and 10 g preparations were also added to the slurry volume of 20 m^3 with the biodynamic preparations.

The three factors—tillage, fertilization and preparations—were fully factorized. This resulted in eight treatments, each replicated four times. The 32 plots were arranged in a strip-plot design. The plot size was 12 m × 12 m, allowing the use of regular-sized farming equipment. Soil samples were taken and yields were measured in an inner 8 m × 8 m parcel.

Site conditions

The soil type at the experimental site was a Stagnic Eutric Cambisol with 45% clay content [coefficient of variance (cv) 15%] and a pH_{H_2O} of 7.1 (cv 4%). It was enriched in ammonia acetate-EDTA extractable P and K due to extensive application of manure from livestock (swine) in pre-study conventional management.

Before the experiment started, the field was under conventional management and had been managed organically for 7 years in accordance with the European Union Regulation (EEC) No. 834/2007. The ploughing depth was 22 cm under conventional farming and 15 cm under organic farming prior to the start of the experiment. C_{org} in the ploughed soil depth was therefore distributed relatively homogeneously.

The mean annual precipitation at the site was 1000 mm. In rainy periods the soil can be waterlogged for some days. The mean annual temperature was 8.9°C.

Crops

A ley-based rotation was established from 2003 to 2008 (Table 1). Cereal and sunflower grains, cereal straw, the oat–clover intercrop, grass–clover and silage maize were removed from the field. In the RT system only a winter pea catch crop was established before silage maize and incorporated in spring.

Cereal yields were 11% lower under RT compared to CT, whereas sunflower yields were increased by 5% under RT[26]. Yields of grass–clover and silage maize were enhanced by 26 and 34%, respectively in RT plots[27].

Soil sampling

Soil samples were taken at the beginning of the experiment on October 1, 2002 (after harvest of silage maize), on March 15, 2005 (standing crop: spelt) and on September 25, 2008 (after harvest of silage maize) in all 32 experimental plots. Twelve individual cores (diameter 3 cm) per field plot were separated into 0–10 cm and 10–20 cm soil depth layers and thereafter bulked to one composite sample per plot and layer. Soils were then sieved through a 5-mm mesh and kept at 3°C until they were analyzed.

Chemical soil analysis

Measurement of pH and C_{org}. The pH of dried samples (60°C, 24 h) was measured in a soil suspension with deionized water (1:10, w/v). C_{org} was measured after wet oxidation of 1 g of dry soil in 20 ml concentrated H_2SO_4 and 25 ml 2 M $K_2Cr_2O_7$ in accordance with Swiss standard protocols[30].

Measurement of soil nutrient contents. Soluble nutrients P and K were extracted with CO_2-saturated water (P_{CO_2}, K_{CO_2}) according to Swiss standard protocols[30].

The plant-available exchangeable fraction of P ($P_{Aac-EDTA}$) was extracted with ammonium acetate-EDTA. Phosphate in the extract was measured after complex formation with added ammonium molybdate in a spectrophotometer at 750 nm. Available K in the ammonium acetate-EDTA extract ($K_{Aac-EDTA}$) was measured by atom absorption spectrometry at 766.5 nm[30].

Soil microbial analyses

All soil microbial analyses were carried out on moist soil samples adjusted to a water content corresponding to 40–50% of maximum water retention capacity.

Chloroform fumigation extraction (CFE). Soil microbial biomass C (C_{mic}) and N (N_{mic}) were estimated by CFE in accordance with Vance et al.[31]. CFE was done in triplicate on 20 g (dry matter) subsamples that were extracted with 80 ml of a 0.5 M K_2SO_4 solution. Total organic C (TOC) in soil extracts was determined by infrared spectrometry after combustion at 850°C (DIMA-TOC 100, Dimatec, 45276 Essen, Germany). Total N was subsequently measured in the same sample by chemoluminescence (TNb, Dimatec, 45276 Essen, Germany). Soil microbial biomass was then calculated according to the formula: $C_{mic} = EC/k_{EC}$, where EC = (TOC in fumigated samples − TOC in control samples) and $k_{EC} = 0.45$[32]. $N_{mic} = EN/k_{EN}$, where EN = (total N extracted from fumigated samples − total N extracted from control samples) and $k_{EN} = 0.54$[33].

Soil DHA. DHA was measured according to Tabatabai[34] in 5 g of soil samples incubated at 30°C for 24 h in the presence of an alternative electron acceptor [triphenyltetrazolium chloride (TTC)]. The red-colored product [triphenylformazan (TPF)] was extracted with acetone and measured in a spectrophotometer at 546 nm.

Nutrient balances

Nutrient balances for N, P and K were calculated on a field basis. Wheat grains and straw, oat–clover intercrop, sunflower seeds, spelt grains and straw, grass–clover, winter pea and silage maize samples were analyzed for nutrient concentrations. Nitrogen was determined after Kjeldahl digestion. For measuring P and K, samples were incinerated at 600°C and the ash extracted with concentrated hydrochloric acid. N and P concentrations were determined photometrically and K via atom absorption spectrometry. Nutrients (N, P and K) in slurry and manure compost were extracted with hydrochloric acid after the samples had been incinerated at 600°C and were analyzed as specified above. Biological N-fixation by legumes, atmospheric deposition, leaching and gaseous emissions of nutrients were not considered in the balances. The winter pea catch crop contained 62 kg N ha^{-1} and was exclusively incorporated into the soil of the RT system. Although it was assumed that the whole quantity of catch crop N was not fixed biologically, it was included in the nitrogen budget.

Statistics

The statistical model used involved tillage as the main factor in the strip-plot design and Fertilization∗Preparations as a combined factor. Soil microbial properties and nutrient contents were calculated with a general linear model to test for significance using SPSS 15.0 software (SPSS Inc., Chicago, Illinois, USA, 2006). Linear contrasts were then calculated for fertilization and preparations using SAS 9.1 software (SAS Institute Inc., Cary, North Carolina, USA, 2002–2003). A mixed model in SAS was used to perform a time line analysis for pH and C_{org} with the fixed factors Tillage, Fertilization∗Preparations and Year (Year as a repeated measure). The Block was used as a random factor. In the result tables, first the means of the eight basic treatments were presented. Second the relative differences between the factors tillage, fertilization and preparation were shown. Third, the significant differences between the three factors and respective interactions were depicted. The levels of probability $P < 0.05$, $P < 0.01$ and $P < 0.001$ were declared significantly different.

Results and Discussion

After the first 6-year crop rotation period of the present experiment, statistical analysis revealed no effects of fertilization and only slight effects of preparations on the investigated properties while the response to tillage was strong, especially in the 0–10 cm soil depth layer. A distinct stratification of C_{org}, microbial biomass C and N, microbial activity, plant-available P and K was found under RT, while they were distributed relatively homogeneously throughout 0–20 cm under CT.

pH and C_{org}

A mixed model analysis of variance (ANOVA) with repeated measures in 2002, 2005 and 2008 was used to identify significant changes of pH and C_{org} over the first crop rotation period. The factors Year in both soil layers and Tillage in the 0–10 cm soil layer showed significant effects. There was no effect of the combined factor Fertilizer∗Preparations. The interaction Year∗Tillage significantly affected pH and C_{org} in the 0–10 cm soil layer (Table 3).

Soil pH deceased significantly from 2002 to 2005 under both tillage treatments and in both soil depths. When compared with the initial values of 2002, pH values in 2008 were significantly lower only under RT (Table 4, Fig. 1). The decrease of pH was highest under RT in 0–10 cm (−0.17, $P < 0.01$).

According to Rasmussen[5], soil acidity under RT increases in the long run by 0.2–0.3 units in topsoil, which may be due to an accumulation of organic acids in the superficial layer[35]. These findings are in agreement with the results of the present experiment. On the other hand, CT may prevent ions from leaching by turning the soil and thus retard acidification of the topsoil[36]. Seasonal differences

Table 4. Means for pH and soil organic carbon (C_{org}) in 2002, 2005 and 2008 in soil depth layers 0–10 cm and 10–20 cm. Results of the mixed model *t*-test for Year∗Tillage, indicating significant differences of the means of each treatment in 2005 and 2008 compared with the corresponding means in 2002.

				pH_{H_2O} 2002		pH_{H_2O} 2005		pH_{H_2O} 2008		C_{org} 2002 (%)		C_{org} 2005 (%)		C_{org} 2008 (%)	
				0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm	0–10 cm	10–20 cm
Treatment															
I	Con	MC	P−	7.59	7.59	7.37	7.41	7.52	7.48	2.08	2.06	2.25	2.24	2.19	2.16
II	Con	MC	P+	7.59	7.55	7.40	7.40	7.52	7.48	2.19	2.07	2.22	2.21	2.27	2.16
III	Con	Slu	P−	7.70	7.65	7.48	7.51	7.63	7.60	2.09	2.02	2.18	2.10	2.11	2.09
IV	Con	Slu	P+	7.61	7.60	7.45	7.42	7.56	7.52	2.09	2.05	2.20	2.22	2.07	2.13
V	Red	MC	P−	7.64	7.58	7.31	7.34	7.44	7.51	2.24	2.23	2.50	2.31	2.69	2.28
VI	Red	MC	P+	7.53	7.54	7.31	7.38	7.35	7.43	2.23	2.15	2.55	2.28	2.60	2.18
VII	Red	Slu	P−	7.66	7.63	7.41	7.43	7.41	7.48	2.12	2.12	2.41	2.33	2.64	2.13
VIII	Red	Slu	P+	7.51	7.59	7.37	7.41	7.44	7.47	2.16	2.15	2.39	2.22	2.51	2.11
Mean				7.60	7.59	7.39	7.41	7.48	7.50	2.15	2.11	2.34	2.24	2.39	2.15
ANOVA Year∗Tillage															
Conventional				–	–	***	***	(*)	n.s.	–	–	*	(*)	n.s.	n.s.
Reduced				–	–	***	**	**	*	–	–	***	(*)	***	n.s.

Con, CT; Red, RT; MC, manure compost; Slu, slurry; P−, without preparations; P+, with preparations.
(*) $P<0.1$; *$P<0.05$; **$P<0.01$; ***$P<0.001$; n.s., not significantly different.

causing the lower levels measured in spring 2005 cannot be excluded.

Under RT C_{org} in the 0–10 cm soil layer in 2008 was 19% higher ($P<0.001$) than the initial values in 2002. This represents an increase from 2.19% C_{org} to 2.61% C_{org} within 6 years. C_{org} remained constant under CT (Fig. 1). No significant differences were found in the 10–20 cm soil layer and there were no effects of fertilization or preparations.

C_{org} is considered an important indicator of soil fertility. The increase in C_{org} in our experiment in the 0–10 cm soil layer under RT measured in 2005[26] continued between 2005 and 2008. In a meta-study, Ogle et al.[37] found C_{org} increased by 16% in 0–30 cm depth after 20 years of NT in a temperate wet climate. Alvarez[4] found no differences in C_{org} accumulation between NT and RT. In this meta-study, the amount of C_{org} integrated over 30 cm soil depth under NT and RT was 14% higher than under CT, if only long-term experiments were taken into account. The increase in C_{org} took place only in the 0–15 cm soil layer, and no differences were reported below 15 cm, which corresponds to our findings. Our results are in line with those of Pekrun and Claupein[2], Rasmussen[5], Kladivko[6] and Koch and Stockfisch[7]. Under organic farming conditions, Emmerling[25] reported a relative increase in C_{org} of 7–10% in the surface layer after 10 years of RT, with no differences below the tilled layer. Other studies found an increase in C_{org} in the superficial layer but a decrease in the untilled soil layers below[3,39,40]. Insufficient plant material left on the field may be a reason for the failure of RT to enhance C_{org}. By contrast, input of organic matter via crop rotation and organic fertilizers in the present experiment were high compared to other RT trials (Table 2). This seems to be important, as Baker et al.[8] argue that C_{org} gains in most cases are based only on near-surface samples (0–30 cm). Changes in C_{org} disappear when deeper sampling (below 30 cm) is included. Under organic farming conditions, Schulz et al.[24] found no increase in C_{org} after 12 years of RT but C_{org} was altered by inducing a ley phase into the crop rotation and with amendment of manure. Many authors[2,41,42] argue that periodical use of moldboard ploughing may be inevitable in organic farming to control weed problems. However, high losses of C_{org} have been reported after single-moldboard ploughing in an RT system, proportional to the previous gain under NT or RT in some studies[7,43,44]. In other studies, no changes could be observed in C_{org} after ploughing of NT soils[45–47]. If periodical intervention is only cultivating or ripping and not ploughing, then most of the previously gained C_{org} could be prevented from mineralization[43]. Organic fertilizers, especially manure, enhance more stable fractions of C_{org}[48,49] and thus C_{org} accumulated under RT in stocked organic farming systems may be more resistant to decomposition after moldboard ploughing than in stockless systems. Peigné et al.[10] think that the combined effect of organic farming and RT could also improve the soil organic matter content and consequently soil nutrient reserves in

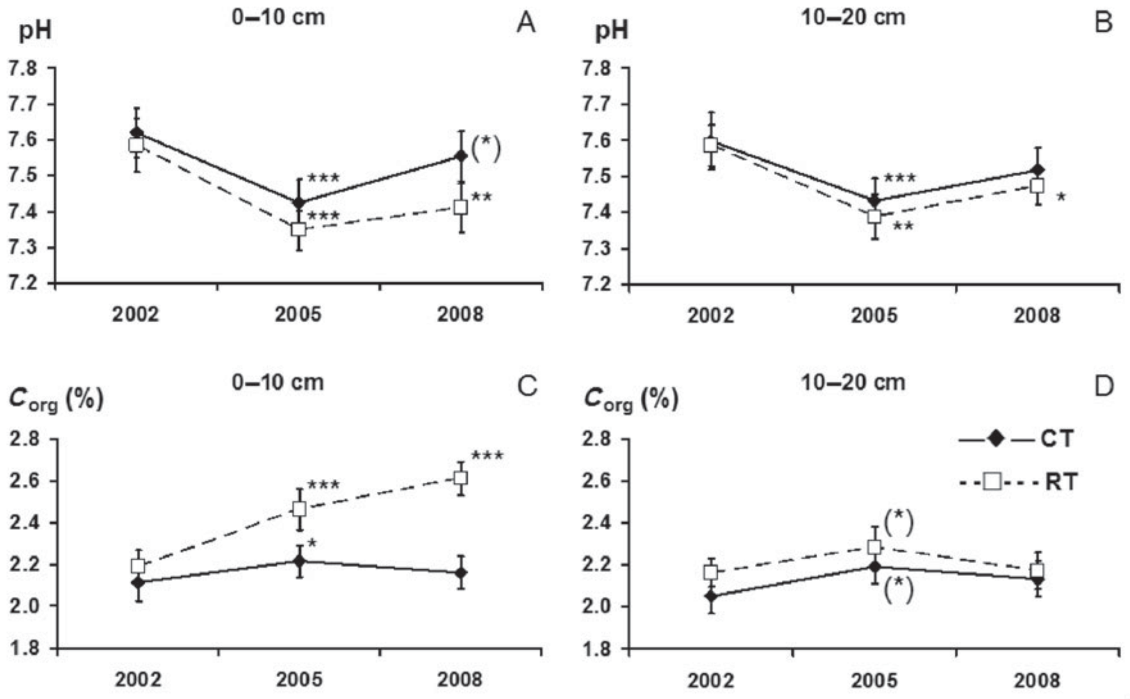

Figure 1. Means and standard error of the mean of pH_{H_2O} and soil organic carbon (C_{org}) in 0–10 cm and 10–20 cm soil depth for RT and CT in the years 2002, 2005 and 2008. A, B: pH. C, D: soil organic carbon [C_{org} (%)]. Results of the mixed model *t*-test for the factor Year∗Tillage, stars indicate significant differences of the means of each treatment in 2005 and 2008 compared with the corresponding mean in 2002. (*) $P < 0.1$, *$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

stockless organic systems and call for further research on this issue.

Soil microbial biomass and activity

Soil microbial biomass (C_{mic}, N_{mic}) and microbial activity (DHA) were highly stratified under RT, whereas they were relatively homogeneously distributed throughout the profile under CT. Soil microbial biomass was greater under RT in the 0–10 cm soil layer, C_{mic} being 37% ($P < 0.01$) and N_{mic} 35% ($P < 0.05$) greater than under CT (Table 5). Under RT, C_{mic} was also greater by 10% ($P < 0.05$) than under CT in the 10–20 cm soil layer, whereas N_{mic} showed no significant difference between the two tillage treatments.

Despite 8% higher average values in the 10–20 cm layer, tillage effects on the C_{mic}-to-N_{mic} ratio were not significant. However, a 7% greater C_{mic}-to-N_{mic} ratio ($P < 0.05$) was found with the use of biodynamic preparations.

The C_{mic}-to-C_{org} ratio, which is considered to be an indicator of biological soil fertility[38,50], was 14% greater ($P < 0.05$) under RT than under CT in the 0–10 cm soil layer. Microbial activity (DHA) was greater by 57% ($P < 0.05$) under RT compared to CT in the 0–10 cm soil depth. In the 10–20 cm layer, DHA was greater under RT by 17% as compared to CT ($P < 0.05$).

Microbial biomass and activity are considered to be early indicators of changes in soil properties induced by tillage regimes[9]. A strong differentiation of the microbial biomass between tilled and untilled layers under RT was found in the present experiment; this corresponds with the results obtained by other authors[9,25,51,52]. While we also found greater microbial biomass C in the 10–20 cm soil layer, others reported no difference[9] in ATP contents[36] or less microbial biomass[25,38] in the untilled layer. Microbial biomass is strongly affected by freshly added organic matter[52]. Friedel et al.[36] accordingly found a high dependence of microbial biomass distribution in the soil on the amount of fresh, decomposable organic matter in a tillage experiment. A clear stratification of the microbial biomass depending on the amount of plant residues in different intense silage maize rotation was found by Franzluebbers and Brock[53]. The high input of organic matter in the Frick trial (Table 2) combined with the reduction of tillage may be the reason for the high levels of microbial biomass C and N, even in the untilled 10–20 cm soil layer. The application of manure in the present experiment—in contrast to the stockless experiment described by Emmerling[25], which was also conducted under organic farming conditions with a ley-based crop rotation—may have been a crucial factor in the dynamics of the microbial populations. Heinze et al.[54] found enhanced microbial biomass as a result of application of manure.

Diversified crop rotations, reduction of tillage and adoption of organic farming are reported to result in a more fungal-dominated microbial community[16]. A higher C_{mic}-to-N_{mic} ratio in the undisturbed 10–20 cm soil depth layer under RT in our experiment supports these findings as it indicates a higher proportion of fungi and older cells in

Table 5. Means of soil microbial biomass C_{mic} and N_{mic}, C_{mic}-to-N_{mic} ratio, C_{mic}-to-C_{org} (%) and DHA in the soil depth layers 0–10 cm and 10–20 cm in 2008, ANOVA for the main effects Tillage and Fertilization∗Preparations, linear contrasts for fertilization and preparations.

				C_{mic} (mg C_{mic} kg^{-1})		N_{mic} (mg N_{mic} kg^{-1})		C_{mic}-to-N_{mic} ratio		C_{mic}-to-C_{org} (%)		DHA (μg TPF g^{-1} d^{-1})	
				0–10 cm	**10–20 cm**	**0–10 cm**	**10–20 cm**	**0–10 cm**	**10–20 cm**	**0–10 cm**	**10–20 cm**	**0–10 cm**	**10–20 cm**
Treatment													
I	Con	MC	P−	891	830	132	126	6.82	6.61	3.79	3.92	395	350
II	Con	MC	P+	782	806	113	125	7.03	6.44	3.45	3.80	331	346
III	Con	Slu	P−	773	774	118	123	6.60	6.31	3.72	3.75	323	337
IV	Con	Slu	P+	758	784	108	122	7.12	6.50	3.71	3.72	304	320
V	Red	MC	P−	1090	881	161	129	6.80	6.86	4.11	3.90	532	384
VI	Red	MC	P+	1038	841	146	123	7.27	6.90	4.03	3.93	459	361
VII	Red	Slu	P−	1023	876	152	128	6.75	6.88	3.93	4.17	499	404
VIII	Red	Slu	P+	1046	878	153	127	6.94	6.98	4.23	4.21	489	380
Mean				925	834	135	125	6.92	6.68	3.87	3.92	417	360
Factor													
Tillage													
Reduced (%) (100% = conventional)				137	110	135	101	102	108	114	107	157	117
Fertilization													
Manure compost (%) (100% = slurry)				101	101	101	101	101	99	97	98	101	97
Preparations													
With (%) (100% = without)				98	99	94	98	107	102	100	99	94	98
ANOVA					#								
Tillage				**	*	*	n.s.	n.s.	(*)	*	(*)	*	*
Preparations				n.s.	n.s.	(*)	n.s.	*	n.s.	n.s.	n.s.	n.s.	n.s.

C_{mic}, soil microbial carbon; N_{mic}, soil microbial nitrogen; C_{org}, soil organic carbon; DHA, dehydrogenase activity; TPF, triphenylformazan.
Con, conventional tillage; Red, RT; MC, manure compost; Slu, slurry; P−, without preparations; P+, with preparations.
No statistically significant differences with factor fertilization and no significant interactions between the factors; # ANOVA for C_{mic} in 10–20 cm depth was calculated with C_{mic}^2-values.
(*) $P < 0.1$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; n.s., not significantly different.

Table 6. Means of nutrient contents in the soil depth layers 0–10 cm and 10–20 cm in 2008, ANOVA for the main factors tillage and Fertilization*Preparations, linear contrasts for fertilization and preparations.

				P_{CO_2} (mg kg^{-1})		$P_{Aac-EDTA}$ (mg kg^{-1})		K_{CO_2} (mg kg^{-1})		$K_{Aac-EDTA}$ (mg kg^{-1})	
				0–10 cm	**10–20 cm**	**0–10 cm**	**10–20 cm**	**0–10 cm**	**10–20 cm**	**0–10 cm**	**10–20 cm**
Treatment											
I	Con	MC	P−	1.93	1.32	112	110	33.6	27.7	479	448
II	Con	MC	P+	1.80	1.14	102	98	31.1	24.3	457	447
III	Con	Slu	P−	1.95	1.20	111	105	30.8	27.4	433	419
IV	Con	Slu	P+	1.62	1.53	106	122	31.7	27.4	447	439
V	Red	MC	P−	3.60	1.46	145	114	44.6	24.4	564	429
VI	Red	MC	P+	3.04	1.26	139	110	43.3	25.5	550	436
VII	Red	Slu	P−	2.81	1.26	132	103	39.9	24.8	546	420
VIII	Red	Slu	P+	3.09	1.56	131	119	50.9	26.5	575	422
Mean				2.48	1.34	122	110	38.2	26.0	506	433
Factor											
Tillage											
Reduced (%) (100% = conventional)				172	107	127	103	140	95	123	97
Fertilization											
Manure Compost (%) (100% = slurry)				109	93	104	96	100	96	102	104
Preparations											
With (%) (100% = without)				93	105	95	104	105	99	100	102
ANOVA											
Tillage				*	n.s.	*	n.s.	(*)	n.s.	*	n.s.
Fertilizer*Preparations				n.s.	n.s.	n.s.	n.s.	(*)	n.s.	n.s.	n.s.

P_{CO_2}, CO_2-extractable phosphorus; K_{CO_2}, CO_2-extractable potassium.
$P_{Aac-EDTA}$, ammonium acetate-extractable phosphorus; $K_{Aac-EDTA}$, ammonium acetate-extractable potassium.
Con, CT; Red, RT; MC, manure compost; Slu, slurry; P−, without preparations; P+, with preparations.
No statistically significant differences with factors fertilizer and preparations.
(*) $P < 0.1$; *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$; n.s., not significantly different.

the total microbial biomass, whereas younger cells and a bacteria-dominated microflora would be reflected in a decrease in the C_{mic}-to-N_{mic} ratio[55]. Guggenberger et al.[56] and Emmerling[25] found an increase in fungi in the upper soil layer under NT and RT. This, however, was not indicated by changes in the C_{mic}-to-N_{mic} ratio in 0–10 cm soil depth in our experiment. The regular use of the roto tiller may have prevented the development of fungal biomass in the tilled layer in our experiment. Additionally, in the experiment described by Emmerling[25], the green fallow and cereal straw were mulched and remained on the field, leaving high amounts of lignin and cellulose as a favorable substrate for the fungal population.

The C_{mic}-to-N_{mic} ratio increased in the present experiment with the use of biodynamic preparations in 0–10 cm. In contrast, Fließbach et al.[12] found a lower C_{mic}-to-N_{mic} ratio for a treatment with compost and biodynamic preparations compared to a manured conventional system. However, they were unable to say whether this effect was caused by composting or by the biodynamic preparations. Minor effects of biodynamic preparations on soil biology properties were found by Carpenter-Boggs et al.[29], when compared with compost without preparations.

The C_{mic}-to-C_{org} ratio in 0–10 cm under RT was 14% greater than that under CT. This difference was already apparent after 3 years of our trial[26] and became smaller than the differentiation by C_{org}. This confirmed the results obtained by Stockfisch et al.[38], who consider the C_{mic}-to-C_{org} ratio to be an early indicator of an enhancement of C_{org}. Angers et al.[40] found a C_{mic}-to-C_{org} ratio three times greater under RT compared to CT in 0–16 cm after 11 years of silage maize rotation and low input of organic matter. An increase in the C_{mic}-to-C_{org} ratio of 16% in the superficial layer was also reported by Emmerling[25].

We measured significantly greater microbial activity (DHA) under RT in both soil layers. Emmerling[25] found soil respiration and alkaline phosphomonoesterase significantly higher in 0–15 cm under RT but no difference in the soil layer below. Similar results were obtained by von Lützow et al.[52] and Kandeler et al.[9]. Von Lützow et al.[52] reported higher microbial biomass and activity in clay soils because the conditions for micro-organisms were more stable, although C_{org} was less accessible to the microbial community.

Phosphorus and potassium

As with C_{org}, microbial biomass and microbial activity, a clear stratification, especially of soluble P_{CO_2} and K_{CO_2}, was found after 6 years under RT. P_{CO_2} in the 0–10 cm soil layer in 2008 was greater by 72% ($P < 0.05$) in RT than in CT plots, while the exchangeable $P_{Aac-EDTA}$ was only greater by 27% ($P < 0.05$) (Table 6). K_{CO_2} was greater by 40% ($P < 0.1$) in RT than in CT in the 0–10 cm layer in 2008

Table 7. Nutrient budgets on a field basis for nitrogen (N), phosphorus (P) and potassium (K) for the first crop rotation period (2003–2008).

				N ($kg\,ha^{-1}\,yr^{-1}$) #			**P ($kg\,ha^{-1}\,yr^{-1}$)**			**K ($kg\,ha^{-1}\,yr^{-1}$)**		
				Input	**Yield**	**Surplus**	**Input**	**Yield**	**Surplus**	**Input**	**Yield**	**Surplus**
Treatment												
I	Con	MC	P−	109	113	−4	29	23	7	153	101	52
II	Con	MC	P+	105	122	−17	30	23	7	150	103	48
III	Con	Slu	P−	109	135	−25	24	27	−3	164	125	39
IV	Con	Slu	P+	107	131	24	24	25	−1	164	116	48
V	Red	MC	P−	112	158	−47	30	27	3	159	139	19
VI	Red	MC	P+	108	157	−50	30	26	3	156	138	18
VII	Red	Slu	P−	114	161	−47	25	28	−3	172	140	32
VIII	Red	Slu	P+	111	154	−43	25	27	−2	171	142	29
Mean				109	141	−32	27	26	1	161	126	36

Values presented are annual means. # Biological nitrogen fixation not considered.
Con, CT; Red, RT; MC, manure compost; Slu, slurry; P−, without preparations; P+, with preparations.

and $K_{Aac-EDTA}$ was greater by +23% ($P < 0.05$). There were no significant tillage effects in the 10–20 cm soil layer and no effects of fertilization or preparations in both layers.

The small differences between the nutrient budgets for P and K in CT and RT cannot be the reason for the high differences in nutrient contents between the two tillage systems. The surplus of K was even greater under CT (Table 7). Yields of forage crops (grass–clover and silage maize) were greater under RT; larger quantities of crop residues and root biomass were also left on the field. Rasmussen[5] reported a significant increase in plant-available P in 0–5 cm soil depth under RT in various studies, while available P in 10–20 cm remained stable or even decreased. A stratification of plant-available P similar to C_{org} was also found by Emmerling[57], whereas the total amount of plant-available P remained constant in 0–25 cm depth. Vu et al.[58] found a concentration of plant-available P in 0–10 cm under NT. A high accumulation of C_{org} was closely related to organic P dynamics, as organic P accumulates only when C availability is high[59]. Plant-available K in the top layer was greater under RT, whereas there were no differences between RT and ploughed soil in 10–20 cm[5].

Nutrient budgets

To ensure both short-term productivity and long-term sustainability, achieving a balance between inputs and outputs of nutrients within the farm system is crucial[17]. As nitrogen fixation by legumes was not considered in our calculation, nitrogen budgets were clearly negative for all treatments. The deficit was $-17\,kg\,N\,ha^{-1}\,yr^{-1}$ in the mean of the CT compared to $-47\,kg\,N\,ha^{-1}\,yr^{-1}$ in the mean of the RT. P input and removal were balanced, while there was a surplus of K in all treatments over the first crop rotation period (Table 7). K surplus in the conventional treatment ($46\,kg\,K\,ha^{-1}\,yr^{-1}$) was twice that in the reduced treatment ($24\,kg\,K\,ha^{-1}\,yr^{-1}$). Removal of N and K under RT was higher, mainly due to the higher yields of grass–clover and silage maize[27].

If biological N-fixation was considered, N-surpluses of up to $60\,kg\,N\,ha^{-1}\,yr^{-1}$[18] could be estimated for organic farms in the UK. In a survey considering 88 European organically managed farms, Watson et al.[17] found an average N surplus of $82\,kg\,ha^{-1}\,yr^{-1}$ for dairy farms.

Stockless organic farms show P-deficits, while farms with livestock can compensate by importing P in additional feed and bedding material[17,18]. Negative balances of P for organic dairy farms in Norway were reported by Steinshamn et al.[60]. P deficits were also reported by Emmerling[57] in a stockless trial with RT under organic farming conditions.

K budgets calculated for organic crop rotations show both surpluses and deficits[17]. Rotations with large return of manure had K surpluses or balanced K budgets, which is also the case in the present experiment.

To summarize, our results are in agreement with current data in the literature whereby stratification of C_{org}, microbial biomass, microbial activity and soil nutrients were often observed after the adoption of RT. In the 10–20 cm soil layer, we found no differences in C_{org} and soil nutrients between the two tillage systems. Interestingly, soil microbial biomass C and microbial activity (DHA) were also higher in the untilled layer of RT. We found no similar results in the literature and assume that comparatively high inputs of organic material via crop rotation and manure were important factors in the present experiment. The goal of our current research is to target the role of soil types, and of clay minerals in particular, and especially the hydraulic dynamics and aeration of tillage systems. The results presented here reflect the situation after 6 years of RT under organic farming conditions. In their review, Kay and VandenBygaart[3] found results of changes in C_{org} obtained by different investigators to be most consistent when measurements were made more than 15 years after initiating the tillage trial. Further development of soil fertility indicators need to be assessed, also with respect to carbon sequestration in an organic farming system with diversified ley-based crop rotation and organic fertilization, as carbon sequestration of RT systems is still a matter of controversy[8]. Further research on the combined effects of organic farming and RT on this issue is necessary.

Conclusions

After the first 6-year crop rotation period, only tillage resulted in significant responses in soil fertility indicators. Hardly any effects of the fertilization treatments and the use of biodynamic preparations were observed. We found a strong stratification of C_{org}, microbial biomass, microbial activity (DHA) and soluble soil nutrients such as P and K in the RT tillage system. Enhancement of these properties in the superficial soil layer under RT, accompanied by 11% higher yields, led to the conclusion that RT is a suitable method for increasing soil fertility in organic farming systems. In conclusion, our RT system has demonstrated its capacity to provide a balanced performance with respect to several ecological services of agro-ecosystems, such as primary production, maintenance of soil fertility and natural resources, and nutrient supply[61]. It has to be pointed out that these results were obtained on a clayey soil and similar studies are needed under different pedo-climatic conditions. Moreover, because RT organic farming systems protect soil and improve nutrient use efficiency, they may be considered for agricultural policy support actions.

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