Available online at www.sciencedirect.com
ScienceDirect
Agriculture, Ecosystems and Environment 118 (2007) 273–284
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming

Andreas Fließbach [a,*], Hans-Rudolf Oberholzer [b], Lucie Gunst [b], Paul Mäder [a]

[a] Research Institute of Organic Agriculture (FiBL), Ackerstrasse, CH-5070 Frick, Switzerland
[b] Agroscope Reckenholz-Tänikon Research Station ART, Reckenholzstrasse 191, CH-8046 Zürich, Switzerland

Received 22 April 2005; received in revised form 9 May 2006; accepted 17 May 2006
Available online 7 July 2006

Abstract

Organic farming systems often comprise crops and livestock, recycle farmyard manure for fertilization, and preventive or biocontrol measures are used for plant protection. We determined indicators for soil quality changes in the DOK long-term comparison trial that was initiated in 1978. This replicated field trial comprises organic and integrated (conventional) farming systems that are typical for Swiss agriculture. Livestock based bio-organic (BIOORG), bio-dynamic (BIODYN) and integrated farming systems (CONFYM) were compared at reduced and normal fertilization intensity (0.7 and 1.4 livestock units, LU) in a 7 year crop rotation. A stockless integrated system is fertilized with mineral fertilizers exclusively (CONMIN) and one control treatment remained unfertilized (NOFERT). The CONFYM system is amended with stacked manure, supplemental mineral fertilizers, as well as chemical pesticides. Manure of the BIOORG system is slightly rotted and in BIODYN it is composted aerobically with some herbal additives. In the third crop rotation period at normal fertiliser intensity soil organic carbon (C_{org}, w/w) in the plough layer (0–20 cm) of the BIODYN system remained constant and decreased by 7% in CONFYM and 9% in BIOORG as compared to the starting values. With no manure application C_{org}-loss was severest in NOFERT (22%), followed by CONMIN together with the systems at reduced fertiliser intensity (14–16%). Soil pH tended to increase in the organic systems, whereas the integrated systems had the lowest pH values. At the end of the third crop rotation period in 1998 biological soil quality indicators were determined. Compared to soil microbial biomass in the BIODYN systems the CONFYM soils showed 25% lower values and the systems without manure application were lower by 34%. Relative to the BIODYN soils at the same fertilization intensity dehydrogenase activity was 39–42% lower in CONFYM soils and even 62% lower in soils of CONMIN. Soil basal respiration did not differ between farming systems at the same intensity, but when related to microbial biomass (qCO_2) it was 20% higher in CONFYM soils and 52% higher in CONMIN as compared to BIODYN, suggesting a higher maintenance requirement of microbial biomass in soils of the integrated systems. The manure based farming systems of the DOK trial are likely to favour an active and fertile soil. Both, C_{org} and biological soil quality indicators were clearly depending on the quantity and quality of the applied manure types, but soil microbial biomass and activities were much more affected than C_{org}.

Keywords: Soil organic matter; Soil microbial biomass; Soil enzymes; Soil basal respiration; Organic farming; Long-term experiment

1. Introduction

The cycling of elements on the farm is a main principle of organic farming systems that are based on three practical pillars: (1) the maintenance and increase of soil fertility by the use of farmyard manure; (2) the omission of synthetic fertilizers and synthetic pesticides; (3) the lower use of high energy consuming feedstuff. Since many soil and crop treatments are also beneficial to the environment without being directly productive, organic but also integrated farmers receive financial support for their environmental services in many countries. Economic performance (Stolze et al., 2000), efficiency calculations (Alföldi et al., 1999),

* Corresponding author. Tel.: +41 62 865 72 25; fax: +41 62 865 72 73.
E-mail address: andreas.fliessbach@fibl.org (A. Fließbach).

0167-8809/$ – see front matter
doi:10.1016/j.agee.2006.05.022

nutrient balances (Berner et al., 1999) and also soil indicators may be used to integrate the diverse management factors to comparable figures. Since organic farms are relying and depending on nutrient transformation processes, soil quality is an important factor of productivity (Bloem et al., 2005; Drinkwater et al., 1998; Mäder et al., 2002; Reganold et al., 1993).

Sustainable management of agricultural land simultaneously aims at maintaining or enhancing food production, reducing the level of production risk, protecting the potential of natural resources and preventing degradation of soils and water quality, while being economically viable and socially acceptable (FAO, 1993; Schjonning et al., 2004). Organic agriculture is contributing to most of the points listed and to a certain extent this is also true for integrated production systems. Soils play a key role in the definition of sustainable land management since they represent the basis of food production. If soils are eroded or degraded to a larger extent, a society may loose its fundament of safety and self-sufficiency (Pimentel et al., 1995; Pretty et al., 2000).

Soil quality has been defined as ‘‘the capacity of a soil to function within ecosystem and land-use boundaries, to sustain biological productivity, maintain environmental quality and promote plant and animal health’’ (Doran and Parkin, 1994). Apart from the inherent soil quality, which is based upon the parent geological material and is rather static, the dynamic soil quality changes in response to human use and management (Carter et al., 1997). Attributes of dynamic soil quality may change in relatively short periods. Soil organic matter (SOM) levels may vary within years, whilst active SOM-fractions like macro- and light fraction-organic matter, soil microbial biomass and microbial functions may change within shorter periods of time. For a sustainable environment it is important to develop new or improve existing land management systems in order to minimize soil erosion, soil degradation, contamination and losses of potentially hazardous elements to the water bodies, the crop, or the atmosphere. No single land management step alone will enhance soil quality, but integrated combinations of land management strategies are suggested to show a considerable potential (Smith et al., 2000).

Carbon stored in soils represents the largest terrestrial carbon pool. Arable soils usually have low soil organic carbon, whereas values are higher under permanent plant cover. Conversion of natural to agricultural land resulted in the loss of 50–100 Pg of soil organic carbon worldwide over the past 200 years (Jarecki and Lal, 2003). With improved management practices carbon stocks of these soils can be restored, at least temporarily, thus removing CO_2 from the atmosphere. However, current estimates of the actual soil C sink capacity are only 50–66% of the cumulative historic C loss (Lal, 2004).

Evaluations of the agricultural impact on soil carbon sequestration emphasize the return of carbon especially by recycling animal manure (Freibauer et al., 2004; Smith et al., 2000). Having passed the digestive tract, manure is enriched in more refractory compounds that can persist as stable soil organic matter associated with clay and silt particles (Paustian et al., 1997). While farmyard manure return to soils has a positive impact on soil carbon, the application of composted manure has further benefits that are carried along with the aerobic decomposition, where less CH_4 develops than in stacked manure (Davis, 2002).

Long-term agroecosystem experiments exist in many countries of the world and together they make the largest database for determining the impacts of management change (Barnett et al., 1995). These experiments are defined as being older than 20 years and study crop production, nutrient cycling and the environmental impacts of agriculture (Rasmussen et al., 1998). Only three long-term field experiments are devoted to study organic farming systems and still exist (Drinkwater et al., 1998; Mäder et al., 2002; Raupp, 2001). In the 1990s several field experiments with long-term focus were started mainly in Europe and North America (http://www.isofar.org).

This paper presents data on the changes in soil organic carbon and pH over 21 years of organic and conventional farming at reduced and normal fertilization intensity. The study also aimed at investigating soil quality in farming systems of the DOK-trial (D: bio-dynamic, O: bio-organic, K: german ‘‘konventionell’’ integrated) at the end of the third 7-year crop rotation period and adds more detailed information to the paper of Mäder et al. (2002), that focuses on yield and soil fertility in some of the DOK-trial treatments.

2. Material and methods

2.1. The field experiment

In 1978 the DOK field experiment, comparing two organic (bio-*D*ynamic and bio-*O*rganic) and two conventional farming systems (‘‘*K*onventionell’’ with and without manure), was set up at Therwil (7°33′E, 47°30′N) in the vicinity of Basle, Switzerland, by Agroscope Reckenholz Tänikon Research Station (ART Zürich Reckenholz) and the Research Institute of Organic Agriculture (FiBL, Frick). The year before the DOK-trial started the area has been cropped with grass-clover. Between 1973 and 1976 alternating field vegetables and grain crops were grown based on integrated production without manure amendment. From 1957 until 1973 a diverse arable crop rotation with three grass-clover ley years and manure amendment was documented.

The soil is a haplic luvisol (sL) (typic Hapludalf) on deep deposits of alluvial loess. The climate is relatively dry and mild with a mean precipitation of 785 mm per year and an annual mean temperature of 9.5 °C. The four farming systems mainly differed in fertilization strategy and plant protection (Table 1). Crop rotation changed slightly at the end of each crop rotation period (Table 2) but was identical

Table 1
Main differences of the farming systems in the DOK long-term field experiment

	Treatments: manure type							
	Bio-dynamic (BIODYN): composted FYM[a] and slurry		Bio-organic (BIOORG): rotted FYM and slurry		Conventional (CONFYM): stacked FYM and slurry		Mineral (CONMIN)	Unfertilized (NOFERT)
Fertilization								
CRP[b] (LU[c] ha^{-1})	0.6	1.2	0.6	1.2	0.6	1.2	Unfertilized	–
CRP (LU ha^{-1})	0.6	1.2	0.6	1.2	0.6	1.2	–	–
CRP (LU ha^{-1})	0.7	1.4	0.7	1.4	0.7	1.4	–	–
Mineral fertilizer	–		Rockdust, K Magnesia		Mineral fertilizer as supplement		Exclusively mineral fertilizer	–
Plant protection								
Weed control	Mechanical				Mechanical and herbicides			Mechanical
Disease control	Indirect methods				Chemical (thresholds)			Indirect
Insect control	Plant extracts, bio-control				Chemical (thresholds)			Plant extracts, bio-control
Special treatments	Biodynamic preparations		$CuSO_4$ in potatoes until 1991		Plant growth regulators			Biodynamic preparations

[a] FYM: farmyard manure.
[b] CRP: crop rotation period.
[c] LU: livestock unit.

for all systems (Besson and Niggli, 1991) and, except for the more frequent mechanical weeding in the organic plots, this was also true for soil tillage.

The bio-dynamic (BIODYN) and the bio-organic (BIOORG) systems received organic fertilizers, whereas organic and supplemental mineral fertilizers were applied in one conventional (CONFYM) system (Table 1). All systems with manure amendment were performed at two fertilization intensities, corresponding to 0.6 and 1.2 livestock units per hectare in the first two crop rotation periods (CRP) and 0.7 and 1.4 in the third CRP. Another treatment with conventional plant protection was left unfertilized during the first CRP, but was then converted to a stockless conventional system with mineral fertilizer only (CONMIN). A control treatment remained unfertilized (NOFERT). The biological systems (BIODYN and BIOORG) received 45–69% of the nutrients (NPK) that were applied to the conventional systems (CONFYM and CONMIN) (Mäder et al., 2002; Niggli et al., 1995).

The organic fertilization was performed with system specific manure types and the fertilization schedule in the organic systems involved smaller and more frequent manure applications than in the conventional system, where the total amount of manure was split to be applied to red beets and

Table 2
Crops and intercrops in the three crop rotation periods of the DOK long-term field experiment[a]

Year of the crop rotation	1. Crop rotation period 1978–1984	2. Crop rotation period 1985–1991	3. Crop rotation period 1991–1998 (*crops at sampling time in 1998*)
1	Potatoes (*Solanum tuberosum*, L.) Green manure	Potatoes Green manure	Potatoes
2	Winter wheat 1 (*Triticum aestivum*, L.) Fodder intercrop	Winter wheat 1 Fodder intercrop	Winter wheat 1 *Sunflower/vetch catchcrop*
3	White cabbage (*Brassica oleracea*, L.)	Beetroots (*Beta vulgaris*, L.)	Beetroots
4	Winter wheat 2	Winter wheat 2	*Winter wheat 2*
5	Winter barley (*Hordeum vulgare*, L.)	Winter barley	Grass-clover 1 STM430[b]
6	Grass-clover 1 STM330[c]	Grass-clover 1 STM330[c]	Grass-clover 2
7	Grass-clover 2	Grass-clover 2	*Grass-clover 3*

[a] Note that three parallel crop rotations are running temporally shifted on the subplots A, B and C (see Fig. 1).
[b] STM430: *Trifolium pratense* L. 3%; *Trifolium repens* L. 11%; *Dactylis glomerata* L. 14%; *Festuca rubra* L. 8%; *Phleum pratense* L. 8%; *Lolium perennne* L. 28%; *Poa pratensis* L. 28%.
[c] STM330: *T. pratense* L. 9%; *T. repens* L. 12%; *D. glomerata* L. 15%; *Festuca pratensis* Huds. 36%; *P. pratense* L. 8%; *L. perennne* L. 18%.

potatoes only. C-to-N ratios of manure and slurry applied to potatoes and winter wheat the year before soil sampling averaged 13 for the bio-dynamic, 18 for the bio-organic and 20 for the conventional system. Twenty-one years of manure amendment at rates corresponding to 1.4 livestock units resulted in an average input of 1.78 Mg organic carbon ha^{-1} $year^{-1}$ to the BIODYN soils, 2.24 Mg to the BIOORG and 2.18 Mg to the CONFYM soils (Corresponding average annual application rates are 11.2, 12.4, and 11.9 Mg fresh manure ha^{-1} and 33.2, 38.5, and 37.2 m^3 slurry ha^{-1} in BIODYN, BIOORG and CONFYM, respectively). Due to the loss on composting, carbon input to the BIODYN soils thus averaged at 18 and 21% lower values than in the corresponding CONFYM and BIOORG soils, respectively.

Plant protection of the BIOORG and BIODYN systems was conducted according to the respective guidelines (Lampkin, 1990). Pesticides in the conventional systems (CONFYM, CONMIN) were mainly applied with respect to economic thresholds (integrated plant protection). Plant protection in the unfertilized treatment was the same as in the BIODYN system. Since the year 1985, the conventional farming systems were managed according to Swiss guidelines for integrated plant production that are similar to those at the European level.

The experiment has a split-split-plot design with four field replicates for each of the three crops planted (Fig. 1). Single plot size is 5 m by 20 m. The experiment was conducted close to agricultural farming practice and in order to ascertain this link, advisory farmer groups were established for each system.

2.2. Soil sampling

Soil samples were taken on 15 March 1998 as a bulked sample from 16 cores of Ø3 cm and 20 cm depth (plough layer) of each of the four field replicates. This resulted in 96 composite soil samples from eight treatments and three crops (grass-clover, the mulched sunflower-vetch catch crop, and winter-wheat 2 in the three subplots A, B and C, respectively). Winter wheat 2 was in the tillering phase, grass-clover in the third year after sowing and the decayed catch crop was mulched 4 days before sampling. Soils were sieved (2 mm) and kept at 4 °C until they were analysed.

Soil samples for the time course of soil organic carbon have been taken from the 0–20 cm soil layer after harvesting the respective annual crop in each plot. Before the beginning of the field experiment, in 1977, samples were only taken as a bulk sample from each of the 16 row–column intersections in order to account for spatial variability. Samples were sieved (2 mm) and air dried. A representative subset of samples from the archive was reanalysed in 2002 and checked for reproducibility and plausibility of the data, especially with respect to the starting values and the temporal trend.

2.3. Measurement of pH, C_{org}, and N_t

The pH of dried samples (60 °C, 24 h) was measured in a soil suspension with deionized water (1:10, w/v). Soil organic carbon was measured spectrophotometrically after wet oxidation of 1 g dry soil in 20 ml concentrated H_2SO_4 and 25 ml 2 M $K_2Cr_2O_7$. Total soil nitrogen was measured

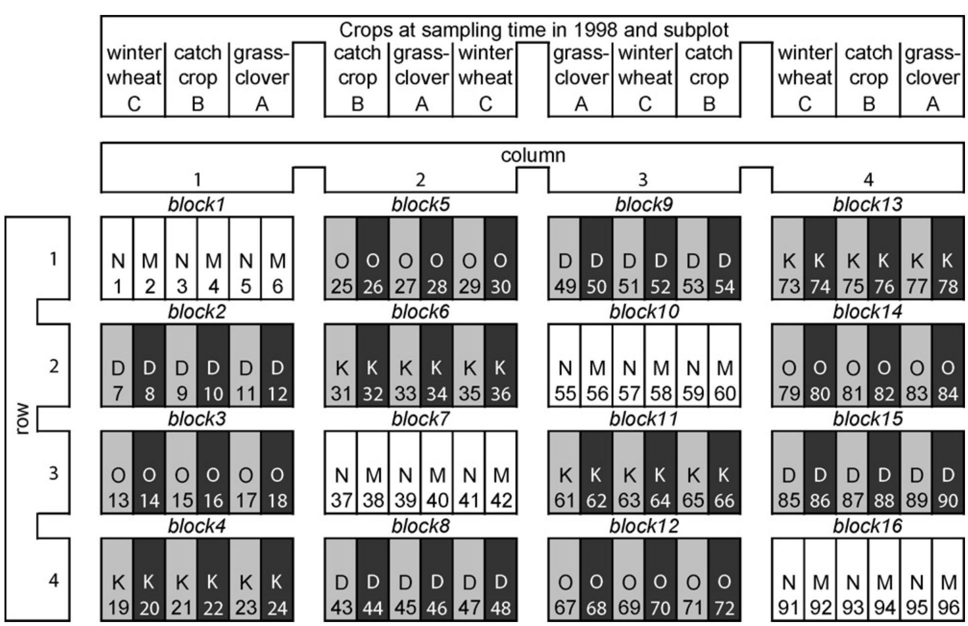

Fig. 1. Field map of the DOK farming systems trial in Therwil (Baselland, Switzerland). N: NOFERT, M: CONMIN, D: BIODYN, O: BIOORG, K: CONFYM, black fields with white letters indicate plots with normal fertilization intensity (1.2 livestock units ha^{-1} (LU) in the first and second crop rotation period (CRP), 1.4 LU ha^{-1} in the third CRP), grey ones reduced intensity (0.6 LU ha^{-1} in the first and second CRP, 0.7 LU ha^{-1} in the third CRP) and those without manure application are white.

after Kjeldahl digestion according to Swiss standard protocols (FAL et al., 1996) in a Skalar flow inject analyzer.

2.4. Soil microbial biomass

All soil biological analyses were done with moist soil samples at a water content corresponding to 40–50% maximum water holding capacity.

2.4.1. Chloroform fumigation extraction

Soil microbial biomass C (C_{mic}) and N (N_{mic}) was estimated by chloroform-fumigation-extraction (CFE) according to Vance et al. (1987). 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, Essen, D). Total N was subsequently measured in the same sample by chemoluminescence (TN_b, Dimatec, Essen, D). Soil microbial biomass was then calculated according to the formula: $C_{mic} = E_C/k_{E_C}$ where E_C = (TOC in fumigated samples − TOC in control samples) and $k_{E_C} = 0.45$ (Joergensen and Mueller, 1996a). $N_{mic} = E_N/k_{E_N}$ where E_N = (N_t in fumigated samples − N_t in control samples) and $k_{E_N} = 0.54$ (Joergensen and Mueller, 1996b).

2.4.2. Substrate induced respiration

A physiological method for estimation of microbial biomass was used according to Anderson and Domsch (1978). Preincubated subsamples were carefully mixed with 3000 mg kg^{-1} glucose. Ten grams of (dry matter) subsamples were weighed into perforated centrifuge tubes fitting exactly to a 250 ml screw bottle (Schott). The tubes were inserted into the screw bottle with 20 ml 0.025N NaOH at the bottom and closed immediately. Four hours later the soil was taken out of the flask and subsequently CO_2 absorbed in the alkali was titrated with 0.025N HCl.

2.5. Soil dehydrogenase activity

Dehydrogenase activity was measured according to Tabatabai (1982) in 5 g soil samples that were incubated at 30 °C for 24 h in the presence of an alternative electron acceptor (triphenyltetrazoliumchloride). The red coloured product (triphenylformazan) was extracted with acetone and measured in a spectrophotometer at 546 nm.

2.6. Soil basal respiration

Soil basal respiration was measured in preincubated (7 days at 22 °C) samples as CO_2 evolved over a period of 72 h. Soil samples (20 g dry matter) were weighed into perforated centrifuge tubes and placed into a screw bottle (Schott, 250 ml) in the presence of 0.025N NaOH as CO_2-trap for a 24 h preincubation period in the bottle. The actual measurement started by adding exactly 20 ml of 0.025N NaOH. Exactly after 48 h the soil was taken out of the bottle and the alkali was titrated with 0.025N HCl. The measurement was done according to the reference methods of the Swiss agricultural research centres (FAL et al., 1996).

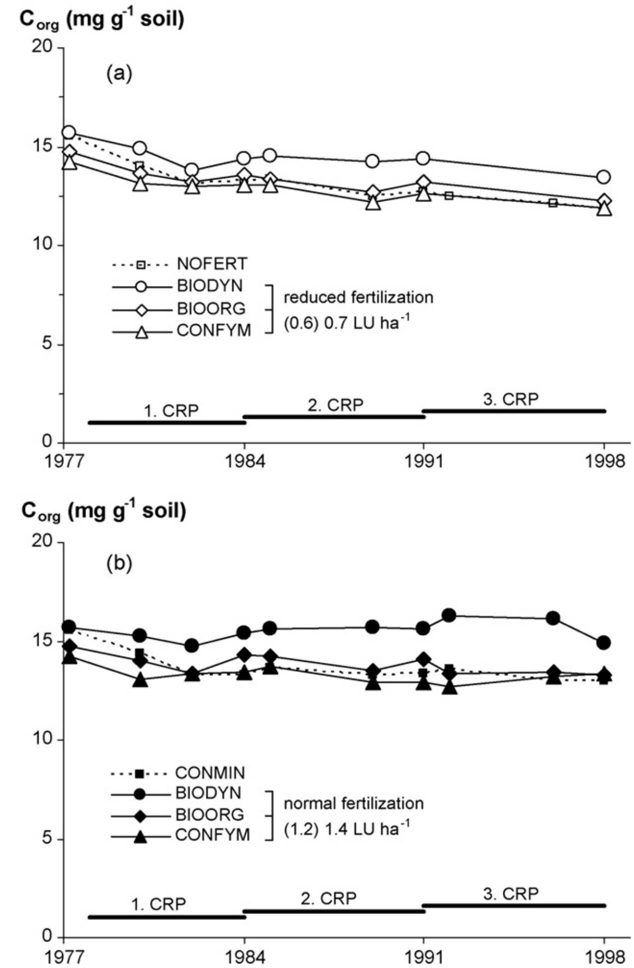

Fig. 2. Soil organic carbon (C_{org}) in the field plots of the DOK farming systems. (a) Systems with reduced fertilization intensity (0.6 livestock units ha^{-1} (LU) in the first and second crop rotation period (CRP), 0.7 LU ha^{-1} in the third CRP) and the unfertilized control (NOFERT). (b) Systems with normal fertilization intensity (1.2 LU ha^{-1} in the first and second CRP, 1.4 LU ha^{-1} in the third CRP) and the conventional system without manure (CONMIN, left unfertilized in the first 7 years). $n = 12$, C_{org} values of 1977-before the plot management-are block means, therefore the two intensities have the same values.

2.7. Data calculation and statistics

Data are presented on a dry matter base if not otherwise stated. Analysis of variance was performed on the whole data set using a multifactorial model with farming system, column, row and crop as factors (JMP, SAS Institute, Cary, NC). The design of the experiment did not allow for including interactions in the model. pH-values were delogarithmized before calculating means and statistics. For the statistical evaluation of farming systems and the fertilization intensity, the two treatments NOFERT and CONMIN were excluded and the multifactorial model comprised farming system, intensity and subplot. With significant model effects, a Tukey Kramer post hoc test was performed to compare the sample means.

3. Results

3.1. Soil organic matter development

Soil organic carbon (C_{org}, w/w) values in the A_p-horizon (0–20 cm) decreased in all farming systems in the first years after the initial setup of the DOK field experiment in 1977 (Fig. 2). Year-to-year variation was relatively small. The standard error for C_{org} among the farming systems replicates, averaged over the years, ranged between 0.25 and 0.81 mg g^{-1} or 1.9 and 5.8%. The highest decrease in C_{org} was found in the unfertilized control (NOFERT) with 24% lower values in 1998 as compared to the initial values in 1977. Farming systems at reduced intensity (Fig. 2a) and the CONMIN system showed a decrease in C_{org} of 15–16%, whereas at normal intensity (Fig. 2b) C_{org} loss varied between 4 and 10%. In 1984 farming system effects became significant for the first time (BIODYN at normal intensity > NOFERT, CONMIN and CONFYM at reduced intensity). It has to be considered that the CONMIN system received the conventional pesticides in the first 7 years, but was left unfertilized. Averaged over each crop rotation period (CRP) C_{org} losses compared to the start were highest in the two systems without manure. CONMIN losses were slightly lower than in NOFERT from the second CRP on and similar to those at reduced fertilization intensity, where average C_{org} losses compared to 1977 varied between 8 and 16% without significant system effects. Fertilization with manure at normal intensity showed the lowest C_{org} losses and even a small gain in the BIODYN system in the third CRP (Table 3).

Total soil N in 1998 accounted for 1.63 mg g^{-1} soil in the BIODYN system at normal fertilization intensity, which was significantly higher than in soils from all the other systems that averaged at 1.39 mg g^{-1} soil. The ratio of soil organic carbon and nitrogen varied only slightly with respect to the farming systems, but under the third year of the grass-clover ley, C-to-N ratio of the soils was significantly ($p = 0.05$) higher than under the other crops (Table 4).

Table 3
Change of average C_{org} values per crop rotation period (CRP) as compared to the initial values in 1977 before the start of the DOK long-term field experiment

	Intensity	1. CRP 1978–1984	2. CRP 1985–1991	3. CRP 1992–1998
NOFERT	No manure	−14% b	−18% c	−22% c
CONMIN	No manure	−12% ab	−14% bc	−15% bc
BIODYN	0.7 LU ha^{-1}	−8% ab	−8% abc	−14% bc
BIOORG	0.7 LU ha^{-1}	−8% ab	−11% bc	−16% bc
CONFYM	0.7 LU ha^{-1}	−8% ab	−11% bc	−16% bc
BIODYN	1.4 LU ha^{-1}	−3% a	0% a	1% a
BIOORG	1.4 LU ha^{-1}	−6% ab	−5% ab	−9% b
CONFYM	1.4 LU ha^{-1}	−6% ab	−7% ab	−7% ab

Different letters indicate significant Tukey HSD differences between farming systems at $p = 0.05$ ($n = 12$; LU: livestock units).

Table 4
Soil organic carbon (C_{org}), soil nitrogen (N_t) and the C-to-N ratio in soil samples from 0 to 20 cm of the DOK trial in 1998

	Intensity	C_{org} in 1998 (mg kg^{-1})	N_t in 1998 (mg kg^{-1})	Soil C-to-N ratio in 1998
NOFERT	No manure	11.83 b	1.33 b	8.92 b
CONMIN	No manure	13.00 b	1.42 b	9.15 ab
BIODYN	0.7 LU ha^{-1}	13.40 ab	1.48 ab	9.09 ab
BIOORG	0.7 LU ha^{-1}	12.25 b	1.35 b	9.06 ab
CONFYM	0.7 LU ha^{-1}	11.89 b	1.33 b	8.99 b
BIODYN	1.4 LU ha^{-1}	14.91 a	1.63 a	9.13 ab
BIOORG	1.4 LU ha^{-1}	13.30 ab	1.43 b	9.28 ab
CONFYM	1.4 LU ha^{-1}	13.34 ab	1.40 b	9.53 a
Significance levels of model effects				
Farming system		<0.0000	<0.0001	0.0054
Crop/subplot		0.1303	0.1228	<0.0001

Significance levels of model effects are shown for farming system and subplot. Different letters indicate significant Tukey HSD differences between farming systems at $p = 0.05$ ($n = 12$).

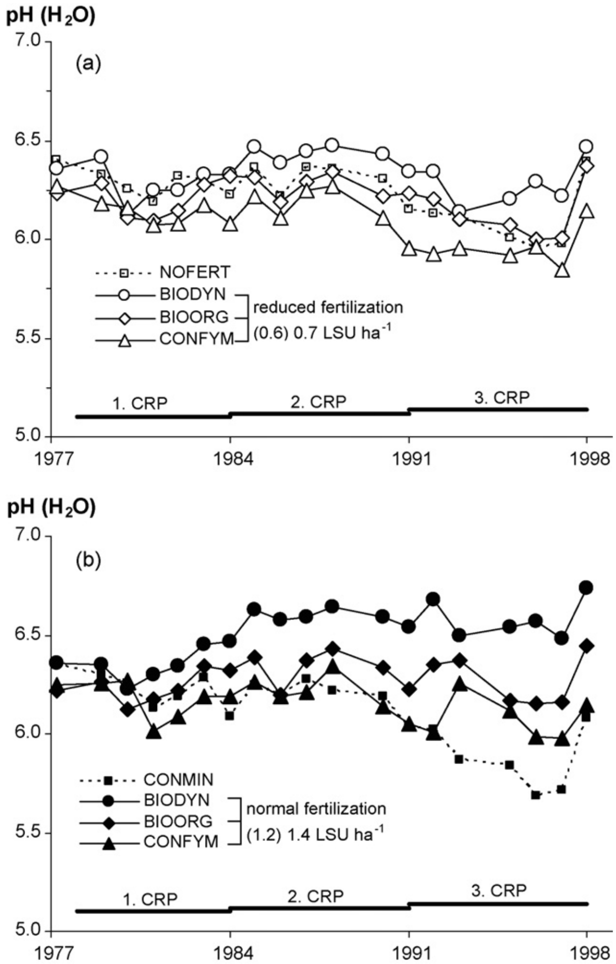

Fig. 3. Soil pH (H_2O) values in the field plots of the DOK farming systems. (a) Systems with reduced fertilization intensity (0.6 livestock units ha^{-1} (LU) in the first and second crop rotation period (CRP), 0.7 LU ha^{-1} in the third CRP) and the unfertilized control (NOFERT). (b) Systems with normal fertilization intensity (1.2 LU ha^{-1} in the first and second CRP, 1.4 LU in the third CRP) and the conventional system without manure (CONMIN, left unfertilized in the first 7 years) ($n = 12$).

3.2. Soil acidity

Soil pH (H_2O) starting values in 1977 ranged at 6.31 without significant farming system effects. Severe year-to-year variation was found, possibly due to short-term crop- and management effect, but the standard error for the replicates of the farming systems averaged over the years only ranged between 0.03 and 0.12 pH-units or 0.42 and 2.05%. First significant effects of the farming systems on soil pH were detected in 1983 and in the forthcoming years. Little variation and only minor differences were found in soils of the unfertilized plots and in farming systems at reduced fertilization intensity (Fig. 3a), whereas in the CONMIN system and at normal intensity soil pH-values were developing in different directions in the farming systems (Fig. 3b). Average pH in the first crop rotation period showed no differences of the farming systems, but was higher in BIODYN systems as compared to all conventional systems (CONFYM and CONMIN) in the second crop rotation period (Fig. 4). In the third crop rotation period CONMIN pH-values decreased by 0.33 pH units, whereas they decreased less sharply in the CONFYM systems and almost remained on the same level in the organic systems.

3.3. Soil microbial biomass

Significant effects of the farming systems and their intensity were found for most of the biological soil parameters. Farming system means of soil microbial biomass carbon (C_{mic}) in 1998 varied between 218 μg g^{-1} soil in the CONMIN system and 360 μg g^{-1} in the BIODYN system (Table 5). The systems with normal fertilization intensity had 10–17% higher C_{mic} values than the reduced input systems, but differences relative to the CONFYM system were hardly affected by the manure input rate. Hence, C_{mic} in the BIODYN soils was 35% and in the BIOORG soils 13–18% higher than in the CONFYM soils.

N_{mic} varied between 32.8 in the CONMIN system and 61.0 μg g^{-1} soil in BIODYN. N_{mic} was distinctly higher in the organic compared to the conventional systems. The effect of the fertilizer intensity on N_{mic} was 21% in the two organic systems, whereas it was only 7.4% in the CONFYM systems (Table 5). Likewise the comparison of N_{mic} between the BIODYN and the CONFYM system resulted in 59% and 44% higher values in the normal and reduced intensity,

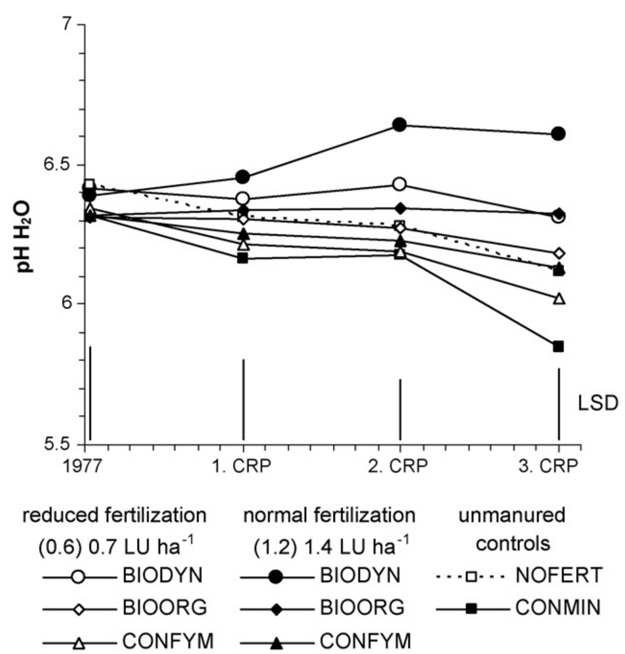

Fig. 4. Average pH (H_2O) values for each crop rotation period (CRP) in comparison to the initial values before the start of the DOK long-term field experiment in 1977. $n = 12$; LSD: least significant difference; LU: livestock units ha^{-1} for the first and second CRP in parentheses and the third CRP.

Table 5
Soil microbial biomass carbon (C_{mic}) and nitrogen (N_{mic}) as estimated by chloroform fumigation extraction (CFE), the ratio of C_{mic} and N_{mic} as an indicator of community structure, and the ratio of C_{mic} and C_{org} as an indicator of soil organic matter quality in soil samples (0–20 cm) of the DOK trial in 1998

	Intensity	C_{mic} (CFE) ($\mu g\ g^{-1}$)	N_{mic} (CFE) ($\mu g\ g^{-1}$)	C_{mic}-to-N_{mic} ratio	C_{mic}-to-C_{org} ratio (mg C_{mic} g^{-1} C_{org})
NOFERT	No manure	235 c	36.1 c	6.61 abc	19.8 b
CONMIN	No manure	218 c	32.8 c	6.84 abc	16.8 c
BIODYN	0.7 LU ha^{-1}	325 a	50.5 b	6.58 abc	24.4 a
BIOORG	0.7 LU ha^{-1}	267 bc	40.7 c	6.63 abc	21.9 ab
CONFYM	0.7 LU ha^{-1}	237 c	34.9 c	6.93 ab	20.0 b
BIODYN	1.4 LU ha^{-1}	360 a	61.0 a	5.95 c	24.2 a
BIOORG	1.4 LU ha^{-1}	313 ab	51.2 b	6.17 bc	23.6 a
CONFYM	1.4 LU ha^{-1}	267 bc	37.6 c	7.24 a	20.1 b
Significance levels of model effects					
Farming system		<0.0001	<0.0001	0.0013	<0.0001
Crop/subplot		0.4717	0.8533	0.0428	0.0006

Significance levels of model effects are shown for farming system and subplot. Different letters indicate significant Tukey HSD differences between farming systems at $p = 0.05$ ($n = 12$).

respectively. Accordingly, the BIOORG system exerted 35% and 16% higher values than the CONFYM system.

The ratio of C_{mic} to N_{mic}, indicative for changes in the microbial community structure, ranged between 5.95 and 7.25. A significant system effect was detected among the systems with normal fertilization intensity. The BIODYN system showed markedly lower values than the CONFYM system. The C_{mic}-to-C_{org} ratio indicates the quality of soil organic matter for microbial biomass establishment. We found this ratio significantly affected by the farming systems, regardless their fertilization intensity. The CONMIN system showed the lowest values, whereas the NOFERT soil had similar figures as both CONFYM soils. BIODYN soils had higher values than the CONFYM soils, indicating a better soil quality; BIOORG soils were taking an intermediate position (Table 5). A significantly higher C_{mic}-to-C_{org} ratio was found under the decaying catch crop as compared to the grass-clover ley and the winter wheat crop.

3.4. Soil microbial activities

The living conditions of microbes are best represented by microbial activities that are bound to the living cell, like basal respiration and endoenzymatic activities. Differences in dehydrogenase activity were clear-cut with respect to the farming systems (BIODYN > BIOORG > CONFYM) and intensity (normal > reduced input > no manure). The subplots, with the decaying sunflower/vetch catchcrop showed the highest values (Table 6).

Basal soil respiration was affected by the farming systems and the crop/subplot. Highest basal respiration was measured in both BIODYN soils and in soils from the systems with normal fertilization intensity-including the CONMIN system. Lowest values were found in the NOFERT system. Basal respiration in the winter wheat subplot was distinctly lower than in the subplots with the catchcrop and the grass-clover subplots. Compared to

Table 6
Soil microbial activity as represented by dehydrogenase activity, soil basal respiration and the metabolic quotient for CO_2 (qCO_2), the quotient of basal respiration and soil microbial biomass in soil samples (0–20 cm) of the DOK trial in 1998

	Intensity	Dehydrogenase activity (μg TPF g^{-1} h^{-1})	Basal respiration ($\mu g\ CO_2\ g^{-1}\ day^{-1}$)	qCO_2 (mg CO_2-C g^{-1} C_{mic} h^{-1})
NOFERT	No manure	103 de	25.2 c	1.24 bc
CONMIN	No manure	87 e	31.8 ab	1.66 a
BIODYN	0.7 LU ha^{-1}	177 b	31.2 ab	1.09 c
BIOORG	0.7 LU ha^{-1}	149 bc	28.5 bc	1.22 bc
CONFYM	0.7 LU ha^{-1}	108 de	27.2 bc	1.32 b
BIODYN	1.4 LU ha^{-1}	226 a	34.5 a	1.10 c
BIOORG	1.4 LU ha^{-1}	175 b	31.6 ab	1.16 bc
CONFYM	1.4 LU ha^{-1}	132 cd	30.5 ab	1.30 b
Significance levels of model effects				
Farming system		<0.0001	<0.0001	<0.0001
Crop/subplot		0.0003	<0.0001	<0.0001

Significance levels of model effects are shown for farming system and subplot. Different letters indicate significant Tukey HSD differences between farming systems at $p = 0.05$ ($n = 12$).

NOFERT, the CONMIN system showed distinctly higher respiration rates, even though both systems were not fertilized with manure (Table 6).

The metabolic quotient for CO_2 (qCO_2) indicates the economy of microbial carbon utilization, which is also connected to the complexity of the microbial food-web in soils. qCO_2 was affected by the farming systems and the crop/subplot. The CONMIN soils showed the highest values and were statistically different from all the other treatments. Lowest values were found for the BIODYN soils regardless their intensity. At both fertilization intensities the CONFYM soils exerted a higher qCO_2 than the BIODYN soils. The winter wheat subplots had significantly lower qCO_2 values than the catch crop before red beets, which again had lower values than the grass-clover plots (Table 6).

4. Discussion

4.1. Soil organic carbon and pH changes over time

An important feature of environmental benefit due to a change in agricultural practice is the soil carbon content (Carter et al., 1997). Loss of soil organic carbon (C_{org}) has often been documented, when cultivation of natural ecosystems began or land use has changed (Tiessen et al., 1982) and in many agricultural long-term experiments-possibly due to more intensive plot management-a decrease in C_{org} has been stated (Barnett et al., 1995). In the first years of the DOK-trial C_{org} decreased in all plots, but there is no evidence so far that the residue return or manure input before the start of the experiment was markedly higher than after. Depending on soil type, climate, management, and the capacity of a soil to store organic matter C_{org} levels may increase linearly with the amount of organic matter input (Carter, 2002; Parton et al., 1996). This part of soil organic matter is usually bound to clay and silt particles and aggregates. Further increases in soil organic matter are likely to be found in particulate organic matter, which is merely part of the sand fraction. In an earlier study using DOK-trial samples, particulate organic matter has been separated into density classes, among which the light fraction represents recently added organic material. The amount of light fraction material was smaller in BIODYN soils with high microbial biomass than in CONMIN soils with low microbial biomass (Fließbach and Mäder, 2000). Differences in residue quality (lignin content or C-to-N ratio) may also influence the level of C_{org} in soils. Likewise, the differences in manure quality were influencing C_{org}-storage in soils of the DOK farming systems, but C_{org}-quality as determined by ^{13}C-NMR appeared to be unaffected (Fließbach et al., 2001). Compared to NOFERT at the end of the 3rd crop rotation period of the DOK-trial, the BIODYN system at normal intensity with an annual manure-compost rate of 18 Mg fresh matter ha^{-1} showed 26% higher C_{org} values. In BIOORG with 22 Mg ha^{-1} a^{-1} fresh manure this increase was 12% and in CONFYM the same amount of fresh manure resulted in 13% higher C_{org}. At reduced fertilization intensity C_{org} increased by 13% in BIODYN, 4% in BIOORG and 1% in CONFYM, thus twice the amount of manure exerted a proportional increase of 9–13% points. These figures are in the range of those given for long-term field experiments on manure applications (Koop, 1993). Since a certain spatial variability in natural soil can never be excluded, internal comparisons to the starting values as well as changes relative to an unfertilized control appear appropriate to calculate changes over time. With farmyard manure applications almost twice as the normal rates in the DOK trial (35 Mg ha^{-1} a^{-1}), C_{org} is still increasing in soils of the Broadbalk wheat experiment (United Kingdom) after 144 years that also has a higher clay content (Smith et al., 1997). Fließbach et al. (1999) showed analyses of C_{org} over the soil profile down to 80 cm in 1998 and found 12.78 kg C_{org} m^{-2} in the BIODYN system and 11.11 kg C_{org} m^{-2} in the CONFYM system. The differences summing up to 1.67 kg C_{org} m^{-2} over the whole soil profile were significant down to a depth of 60 cm. For calculating area values for C_{org} the whole soil profile down to a depth, where no changes are observable, should be analysed, because otherwise soils with a lower bulk density or improved soil structure as a result of increasing C_{org} values would be rated poorer and compacted soils would get a premium. More analyses of C_{org} combined with bulk density measurements over the whole soil profile are needed in order to provide reliable area based C_{org} data.

In the Rodale farming systems trial (Pennsylvania, USA), between 1981 and 2002 C_{org} in the top 30 cm increased by 21.6 Mg ha^{-1} in a manure based organic system, by 12.1 Mg ha^{-1} in a legume based organic system and by only 6.2 Mg ha^{-1} in a conventional system, a maximum gain of roughly 14.4 Mg ha^{-1} C_{org} after 21 years (Drinkwater et al., 1998; Pimentel et al., 2005). Higher C_{org} values in organic farming fields have also been reported for farm comparisons (Reganold, 1988, 1995) but in a Swiss survey of 24 paired organic and conventional winter cereal fields, C_{org} was not significantly different (Oberholzer et al., 2000).

Since composting of farmyard manure is the most substantial difference between the BIODYN system and the other manured systems, the higher C_{org} figures may be due to the higher degree of organic matter stability in mature farmyard manure compost, as compared to uncomposted manure used in BIOORG and CONFYM. Even though starting values for the farming systems were not significantly different, the systems NOFERT, CONMIN and BIODYN had 6–7% higher C_{org} values than BIOORG and CONFYM. This difference is reflecting the site heterogeneity that was found for soil organic matter in 1977. On the other hand the unmanured systems NOFERT and CONMIN showed the highest loss rates and started from the same C_{org} level as the BIODYN systems with relatively stable figures. Stable C_{org} values were also found in the long-term fertilization trial in Darmstadt (D) on a sandy luvisol, when composted manure

Table 7
Soil microbial biomass in soils of the DOK farming systems trial as determined by substrate induced respiration (SIR) in subplots A, B, and C in the years 1990, 1991 and 1998

Farming system	Intensity	Subplot A	Subplot B		Subplot C		Subplots ABC
		1998 (grass-clover, third year)	1990 (winter wheat)	1998 (catch crop)	1991 (winter wheat)	1998 (winter wheat)	1998
NOFERT	no manure	243 b	208 c	237 d	234 c	219 cd	233 ef
CONMIN	no manure	210 b	241 bc	254 cd	263 c	194 d	219 f
BIODYN	0.7 LU ha^{-1}	290 ab	n.d.	369 ab	n.d.	340 abc	333 bc
BIOORG	0.7 LU ha^{-1}	278 ab	n.d.	335 bc	n.d.	277 bcd	297 bcd
CONFYM	0.7 LU ha^{-1}	222 b	n.d.	262 cd	n.d.	238 cd	241 def
BIODYN	1.4 LU ha^{-1}	366 a	412 a	435 a	458 a	403 a	401 a
BIOORG	1.4 LU ha^{-1}	305 ab	314 b	387 ab	389 ab	376 ab	356 ab
CONFYM	1.4 LU ha^{-1}	291 ab	271 bc	292 bcd	339 bc	285 abcd	289 cde
		$n = 4$	$n = 4$	$n = 4$	$n = 4$	$n = 4$	$n = 12$

$SIR_{(1990)} = 24.16 + 0.83 \times SIR_{(1998)}$, $R^2 = 0.813$; $SIR_{(1991)} = 69.18 + 0.91 \times SIR_{(1998)}$, $R^2 = 0.882$.

was applied at similar rates as in the DOK trial (Raupp, 2001). Organic amendments and composts in particular, showed beneficial effects on soil quality in the short (Carpenter-Boggs et al., 2000; Stamatiadis et al., 1999) and longer term (Delschen, 1999; Leifeld et al., 2002; Smith et al., 1997).

One has to consider that all the DOK farming systems are performed according to good farming practice being in line with government programs and subsidies. Especially the fact that most Swiss farms are dairy farms that recycle their own cattle manure also on arable land needs to be considered. The moderate mineral fertilization and pesticide input resulting in modest wheat yields (Dubois et al., 1999; Mäder et al., 2002) renders also the integrated systems sustainable and may be one reason for relatively small differences between soil organic matter dynamics of the BIOORG and the CONFYM system.

4.2. Farming system effects on soil biology

In the long-term, the farming systems of the DOK-trial changed biological soil parameters markedly (Mäder et al., 2002). Soil microbial biomass and indicators of microbial activity were significantly affected by farming systems and fertilization intensity. When omitting the treatments without manure in the statistical model in order to account for intensity effects, the normal manure application rate gave 13% more C_{mic}, 19% more N_{mic}, 23% higher dehydrogenase activity and 11% higher basal respiration than the reduced intensity. Compared to the intensity effect the farming system exerted greater effects: BIODYN had 37% more C_{mic} than CONFYM, 45% more N_{mic}, 64% higher DHA but basal respiration had no significant difference. Therefore it may be concluded that the manure application rate is not as effective for biological soil quality as the farming system, among which manure quality is an important point, but the effects of pesticides and mineral fertilizers cannot be excluded. Interestingly, the ratio of C_{mic}-to-C_{org}, an indicator of soil organic matter quality (Anderson and Domsch, 1989; Fließbach et al., 1994; Moore et al., 2000), does not show an intensity effect, but 22% higher values in BIODYN compared to CONFYM. The qCO_2, which is indicating the maintenance requirement of the microbial biomass, was behaving in a similar way: BIODYN soils regardless their fertilization intensity showed 21% lower values than CONFYM. This means the micro-organisms in BIODYN soils need less energy to maintain their biomass than the ones in CONFYM soils. Comparatively low qCO_2 values are a typical feature of diverse and highly interrelated communities (Anderson and Domsch, 1993).

The actual crop also had a significant influence on basal respiration, with 22% higher values in subplots A (grass-clover third year) and B (catch crop before red beets) as compared to subplot C under winter wheat. Therefore, we assume that basal respiration is affected to a larger extent by recent management changes or the actual crop than is microbial biomass. Likewise, Carpenter-Boggs et al. (2000) found almost 50% more microbial biomass in their 2-year study on compost in comparison to mineral fertilization, whereas basal soil respiration increased by 200%.

Earliest estimates of soil microbial biomass in the DOK trial, based on substrate induced respiration, were done at the end of the second crop rotation period in 1990 and 1991 (Mäder et al., 1993) under winter wheat in early spring. When comparing these microbial biomass figures with those from 1998 the results correlate closely ($r^2 = 0.89$ for 1991 and $r^2 = 0.82$ for 1990) (Table 7). However, the absolute values in 1990 are 83% and 1991 are 91% of those measured in 1998. Hence the differences in soil microbial biomass may have developed earlier than 1990. Soil microbial biomass values, when analysed in the same season and under the same crop, appear to be relatively robust towards short-term effects, thus mainly indicating long-term trends.

5. Conclusions

Soil organic matter in farming systems of the DOK trial was positively affected by manure amendment after 21 years of plot management. Farming systems without manure showed the severest loss in soil organic matter over time. Manure amendment to soils, as an attribute of mixed farming systems, is proven again to exert positive effects.

Biological parameters of soil quality were generally enhanced in organic farming systems as compared to integrated and partly they were positively affected by the application rate of manure. The effects on soil quality in the bio-organic system, which represents the majority of Swiss organic farms, were less pronounced, but for most soil biological parameters this system took an intermediate position between the bio-dynamic and the integrated system. Microbial biomass and activities were enhanced in organic systems emphasizing the important role of element cycling processes that are supported by an abundant and active soil biological community.

Crop rotation and soil tillage were identical in all DOK farming systems. This field experiment thus emphasizes the role of fertilization and plant protection. More work has to be done to investigate single management effects and their combinations on soil organic matter and the soil microbial community to evaluate the environmental role and value of different farming systems.

Acknowledgements

We thank David Dubois, Urs Niggli, and Padrout Fried for their commitment to the DOK field experiment. The work of Werner Stauffer as the head of the field equipe and Robert Frei is gratefully acknowledged. Due to the permanent support of farmers and the advisory group, the DOK trial is representing current farming practice. Expert technical assistance has been provided by Vit Fejfar (FiBL) and Susanne Müller (Agroscope Reckenholz-Tänikon). The DOK long-term experiment has been funded by the Swiss Agricultural Office and research presented in this paper has received support by the Swiss National Science Foundation.

References

Alföldi, T., Schmid, O., Gaillard, G., Dubois, D., 1999. IP- und Bio-produktion: Ökobilanzierung über eine Fruchtfolge. Agrarforschung 6, 305–308.

Anderson, J.P.E., Domsch, K.H., 1978. A physiological method for the quantitative measurement of microbial biomass in soils. Soil Biol. Biochem. 10, 215–221.

Anderson, T.H., Domsch, K.H., 1993. The metabolic quotient for CO_2 (qCO_2) as a specific activity parameter to assess the effects of environmental conditions, such as pH, on the microbial biomass of forest soils. Soil Biol. Biochem. 25, 393–395.

Anderson, T.H., Domsch, K.H., 1989. Ratios of microbial biomass carbon to total organic carbon in arable soils. Soil Biol. Biochem. 21, 471–479.

Barnett, V., Payne, R., Steiner, R., 1995. Agricultural sustainability. In: Economic Environmental and Statistical Considerations, John Wiley and Sons Ltd., Chichester, UK, 266 p.

Berner, A., Heller, S., Mäder, P., 1999. Nährstoffbilanzen im biologischen Landbau. In: Hoffmann, H., Müller, S. (Eds.), Wissenschaftstagung zum ökologischen Landbau, 5. Humboldt-Universität Berlin, Köster, Berlin, pp. 226–229.

Besson, J.-M., Niggli, U., 1991. DOK-Versuch: Vergleichende Langzeit Untersuchungen in den drei Anbausystemen biologisch-Dynamisch, Organisch-biologisch und Konventionell. I. Konzeption des DOK-Versuchs: 1. und 2. Fruchtfolgeperiode. Schweizerische Landwirtschaftliche Forschung 31, 79–109.

Bloem, J., Hopkins, D.W., Benedetti, A., 2005. Microbiological Methods for Assessing Soil Quality. CAB International, Wallingford, 320 p.

Carpenter-Boggs, L., Kennedy, A.C., Reganold, J.P., 2000. Organic and biodynamic management—effects on soil biology. Soil Sci. Soc. Am. J. 64, 1651–1659.

Carter, M.R., 2002. Soil quality for sustainable land management: organic matter and aggregation interactions that maintain soil functions. Agron. J. 94, 38–47.

Carter, M.R., Gregorich, E.G., Anderson, D.W., Doran, J.W., Janzen, H.H., Pierce, F.J., 1997. Concepts of soil quality and their significance. In: Gregorich, E.G., Carter, M.R. (Eds.), Soil Quality for Crop Product. Elsevier Science Publisher, Amsterdam, Netherlands, pp. 1–19.

Davis, J., 2002. Livestock Manure Impacts on Carbon Cycling. http://www.colostate.edu/Depts/SoilCrop/extension/Newsletters/2002/May/Mayweb/may09.html.

Delschen, T., 1999. Impacts of long-term application of organic fertilizers on soil quality parameters in reclaimed loess soils of the Rhineland lignite mining area. Plant Soil 213, 43–54.

Doran, J.W., Parkin, T.B., 1994. Defining and assessing soil quality. In: Doran, J.W., Coleman, D.C., Bezdicek, D.F., Stewart, B.A. (Eds.), Defining Soil Quality for a Sustainable Environment. Soil Science Society of America, American Society of Agronomy, Madison, Wisconsin USA, pp. 3–21.

Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262–264.

Dubois, D., Gunst, L., Fried, P.M., Stauffer, W., Spiess, E., Mäder, P., Alföldi, T., Fließbach, A., Frei, R., Niggli, U., 1999. DOK-Versuch: Ertragsentwicklung und Energieeffizienz. Agrarforschung 6, 71–74.

FAL, FAW, RAC, 1996. Referenzmethoden der Eidg. landwirtschaftlichen Forschungsanstalten. 1. Bodenuntersuchung zur Düngeberatung, Zürich-Reckenholz.

FAO, 1993. World soil resources. An explanatory note on the FAO World Soil Resources Map at 1:25 000 000 scale, Rom. 71 p.

Fließbach, A., Eyhorn, F., Mäder, P., Rentsch, D., Hany, R., 2001. DOK long-term farming systems trial: Microbial biomass, activity and diversity affect the decomposition of plant residues. In: Rees, R.M., Ball, B.C., Campbell, C.D., Watson, C.A. (Eds.), Sustainable Management of Soil Organic Matter. CABI, London, pp. 363–369.

Fließbach, A., Imhof, D., Brunner, T., Wüthrich, C., 1999. Tiefenverteilung und zeitliche Dynamik der mikrobiellen Biomasse in biologisch und konventionell bewirtschafteten Böden. Regio Basiliensis 3, 253–263.

Fließbach, A., Mäder, P., 2000. Microbial biomass and size-density factions differ between soils of organic and conventional agricultural systems. Soil Biol. Biochem. 32, 757–768.

Fließbach, A., Martens, R., Reber, H.H., 1994. Soil microbial biomass and microbial activity in soils treated with heavy metal contaminated sewage sludge. Soil Biol. Biochem. 26, 1201–1205.

Freibauer, A., Rounsevell, M.D.A., Smith, P., Verhagen, J., 2004. Carbon sequestration in the agricultural soils of Europe. Geoderma 122, 1–23.

Jarecki, M., Lal, R., 2003. Crop management for soil carbon sequestration. Crit. Rev. Plant Sci. 22, 471–502.

Joergensen, R.G., Mueller, T., 1996a. The fumigation extraction method to estimate soil microbial biomass: calibration of the k_{E_C}-factor. Soil Biol. Biochem. 28, 25–31.

Joergensen, R.G., Mueller, T., 1996b. The fumigation extraction method to estimate soil microbial biomass: calibration of the k_{E_N}-factor. Soil Biol. Biochem. 28, 33–37.

Koop, W., 1993. Der Einfluss unterschiedlicher Düngerarten (mineralisch, organisch, biologisch-dynamisch) auf bodenmikrobiologische Indikatoren und Parameter der N- und C-Dynamik im Feldversuch und in Laboratoriumsversuchen. In: Fachbereich Agrarwissenschaften. Justus-Liebig-Universität, Giessen.

Lal, R., 2004. Soil carbon sequestration impacts on global climate change and food security. Science 304, 1623–1627.

Lampkin, N., 1990. Organic Farming. Farming Press, Ipswich, 701 p.

Leifeld, J., Siebert, S., Kögel-Knabner, I., 2002. Changes in the chemical composition of soil organic matter after application of compost. Eur. J. Soil Sci. 53, 299–309.

Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P., Niggli, U., 2002. Soil fertility and biodiversity in organic farming. Science 296, 1694–1697.

Mäder, P., Pfiffner, L., Jäggi, W., Wiemken, A., Niggli, U., Besson, J.-M., 1993. DOK-Versuch: Vergleichende Langzeit-Untersuchungen in den drei Anbausystemen biologisch-Dynamisch, Organisch-biologisch und Konventionell III. Boden: Mikrobiologische Untersuchungen. Schweizerische Landwirtschaftliche Forschung 32, 509–545.

Moore, J.M., Klose, S., Tabatabai, M.A., 2000. Soil microbial biomass carbon and nitrogen as affected by cropping systems. Biol. Fertil. Soils 31, 200–210.

Niggli, U., Alföldi, T., Mäder, P., Pfiffner, L., Spiess, E., Besson, J.-M., 1995. DOK-Versuch: Vergleichende Langzeit-Untersuchungen in den drei Anbausystemen biologisch-dynamisch, organisch-biologisch und konventionell. VI. Synthese, 1. und 2. Fruchtfolgeperiode. Schweizerische Landwirtschaftliche Forschung DOK-Sonderheft 4, 1–34.

Oberholzer, H.-R., Nowack, K., Mäder, P., 2000. Soil microbiological aspects in winter cereal fields of organic and integrated farms. In: Alföldi, T., Lockeretz, W., Niggli, U. (Eds.), Proceedings of the 13th IFOAM, Scientific Conference ‘‘The World Grows, Organic’’, Basel, 15 pp.

Parton, W.J., Ojima, D.S., Schimel, D.S., 1996. Models to evaluate soil organic matter storage and dynamics. In: Carter, M.R., Stewart, B.A. (Eds.), Structure and Organic Matter Storage in Agricultural Soils. Lewis Publishers, CRC Press, Boca Raton, FL, pp. 421–448.

Paustian, K., Collins, H.P., Paul, E.A., 1997. Management controls on soil carbon. In: Paul, E.A., Paustian, K., Elliott, E.T., Cole, C.V. (Eds.), Soil Organic Matter in Temperate Agroecosystems. CRC Press, Boca Raton, Florida, pp. 15–49.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Christ, S., Shpritz, L., Fitton, L., Saffouri, R., Blair, R., 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267, 1117–1123.

Pimentel, D., Hepperly, P., Hanson, J., Douds, D., Seidel, R., 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. Bioscience 55, 573–582.

Pretty, J.N., Brett, C., Gee, D., Hine, R.E., Mason, C.F., Morison, J.I.L., Raven, H., Rayment, M.D., van der Bijl, G., 2000. An assessment of the total external costs of UK agriculture. Agric. Syst. 65, 113–136.

Rasmussen, P.E., Goulding, K.W.T., Brown, J.R., Grace, P.R., Janzen, H.H., Körschens, M., 1998. Long-term agroecosystem experiments: assessing agricultural sustainability and global change. Science 282, 893–896.

Raupp, J., 2001. Manure fertilization for soil organic matter maintenance and its effects upon crops and the environment, evaluated in a long-term trial. In: Rees, R.M., Ball, B.C., Campbell, C.D., Watson, C.A. (Eds.), Sustainable Management of Soil Organic Matter. CABI, London, pp. 301–308.

Reganold, J.P., 1988. Comparison of soil properties as influenced by organic and conventional farming systems. Am. J. Altern. Agric. 3, 144–154.

Reganold, J.P., 1995. Soil quality and profitability of biodynamic and conventional farming systems: a review. Am. J. Altern. Agric. 10, 36–45.

Reganold, J.P., Palmer, A.S., Lockhart, J.C., Macgregor, A.N., 1993. Soil quality and financial performance of biodynamic and conventional farms in New Zealand. Science 260, 344–349.

Schjonning, P., Elmholt, S., Christensen, B.T., 2004. Soil quality management, synthesis. In: Schjonning, P., Elmholt, S., Christensen, B.T. (Eds.), Managing Soil Quality: Changes in Modern Agriculture. pp. 315–333.

Smith, P., Powlson, D.S., Glendining, M.J., Smith, J.U., 1997. Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. Glob. Change Biol. 3, 67–79.

Smith, P., Powlson, D.S., Smith, J.U., Falloon, P., Coleman, K., 2000. Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. Glob. Change Biol. 6, 525–539.

Stamatiadis, S., Werner, M., Buchanan, M., 1999. Field assessment of soil quality as affected by compost and fertilizer application in a broccoli field (San Benito County, California). Appl. Soil Ecol. 12, 217–225.

Stolze, M., Piorr, A., Häring, A., Dabbert, S., 2000. The environmental impact of organic farming in Europe. In: Organic Farming in Europe, Economics and Policy, Hago Druck and Medien, Karlsbad-Ittersbach, Germany, Hohenheim.

Tabatabai, M.A., 1982. Soil Enzymes. In: Page, A.L., Miller, R.H., Keeney, D.R. (Eds.), Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. American Society of Agronomy Soil Science Society of America, Madison, Wisconsin, pp. 903–947.

Tiessen, H., Stewart, J.W.B., Bettany, J.R., 1982. Cultivation effect on the amounts and concentrations of carbon, nitrogen and phosphorus in grassland soils. Agron. J. 74, 831–835.

Vance, E.D., Brookes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem. 19, 703–707.