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REPORT

Organic Farming and Soil Carbon Sequestration: What Do We Really Know About the Benefits?

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Abstract Organic farming is believed to improve soil fertility by enhancing soil organic matter (SOM) contents. An important co-benefit would be the sequestration of carbon from atmospheric CO_2. Such a positive effect has been suggested based on data from field experiments though many studies were not designed to address the issue of carbon sequestration. The aim of our study was to examine published data in order to identify possible flaws such as missing a proper baseline, carbon mass measurements, or lack of a clear distinction between conventional and organic farming practices, thereby attributing effects of specific practices to organic farming, which are not uniquely organic. A total of 68 data sets were analyzed from 32 peer-reviewed publications aiming to compare conventional with organic farming. The analysis revealed that after conversion, soil C content (SOC) in organic systems increased annually by 2.2% on average, whereas in conventional systems SOC did not change significantly. The majority of publications reported SOC concentrations rather than amounts thus neglecting possible changes in soil bulk density. 34 out of 68 data sets missed a true control with well-defined starting conditions. In 37 out of 50 cases, the amount of organic fertilizer in the organic system exceeded that applied in the compared conventional system, and in half of the cases crop rotations differed between systems. In the few studies where crop rotation and organic fertilization were comparable in both systems no consistent difference in SOC was found. From this data analysis, we conclude that the claim for beneficial effects of organic farming on SOC is premature and that reported advantages of organic farming for SOC are largely determined by higher and often disproportionate application of organic fertilizer compared to conventional farming.

Keywords Agriculture · Organic farming · Carbon sequestration · Organic fertilizer

INTRODUCTION

Farming practices are known to exert strong control over soil organic carbon (SOC) content because they affect both input and turnover rates of soil organic matter (SOM). Whether particular practices lead to either an increase or a decrease in SOM content has implications for environmental policy, in particular with respect to soil C sequestration. Measures that offset some of the anthropogenic CO_2 emissions could mitigate global warming (Lal 2004). Soil carbon sequestration is a key measure in agriculture and may counterbalance large proportions of agriculturally induced emissions of methane and nitrous oxide (UNFCCC 2008).

However, inconsistent effects are often reported for particular agricultural practices. This may be due to factors other than effects of current management, for example legacy of previous land-use where underlying long-term trends in SOC may modify or even superimpose management-induced trends (Leifeld et al. 2009; Smith et al. 2007). Also, a given management practice or type of management may include various individual activities which jointly affect SOC levels. The latter is typical for so-called organic farming practices. Organic farming consists of a variety of measures that together constitute the 'organic' farming type. The goal of organic farming is to provide high-quality food with minimum environmental impacts in a sustainable way of production. With respect to soil, important aspects of organic farming are diverse crop rotations, cropping of legumes to supply the farm with nitrogen, low external inputs of nutrients, and abandonment of mineral fertilizers and synthetic chemicals used in conventional agriculture for crop protection. These requirements and prohibitions are part of national and supra-national regulations on organic farming (EEC 1991; IFOAM 2006; USDA 1990). Owing to largely reduced external nutrient inputs such as nitrogen, compared to conventional farming, organic farms are often mixed systems including arable crops, forage cropping, and livestock where manure from the latter is returned to the soil. The need for symbiotic nitrogen fixation and forage cropping usually necessitates crop rotations which are generally more diverse than rotations in conventional agriculture.

Organic farming has been shown to increase the SOC contents. Therefore, it is suggested as a measure to improve the overall greenhouse gas balance of agriculture compared to conventional farming (Drinkwater et al. 1998; Liebig and Doran 1999; Niggli et al. 2009; Wells et al. 2000). However, this view is not undisputed as some studies have shown no or no consistent effect on SOC (Friedel 2000; Shannon et al. 2002; Marinari et al. 2006). Crop rotation and organic fertilization are both known to exert strong control over SOC in any farming system, but neither of them is uniquely organic farming. One systematic difference is the higher degree of specialisation of conventional farming, leading to a higher spatial segregation of husbandry and cash crop agriculture. With respect to soil carbon it follows that an unbiased comparison of management types should be based on similar crop rotations and organic fertilization rates or, if rotation and farm type are different, the difference in the system boundary should be considered in the interpretation of the data. Under similar conditions regarding crop rotation and manuring, practices unique to organic farming are the abandonment of external inputs of mineral fertilizers and synthetic chemicals for weed and pest control. Both factors may influence SOC by altering the amount of plant residues available for SOC build-up.

In order to reveal possible contradictions in the reported effects of organic farming on SOC, and to elucidate underlying mechanisms, a rigorous separation of factors that influence SOC dynamics in field experiments is needed. The aim of this study was to analyze published studies that compared SOC in organic and conventional farming systems, to identify ways by which conventional and organic systems differed, and to discuss potential drivers for changes and differences between systems in SOC. In view of a testable hypothesis, we also evaluated the scientific quality and validity of available data sets by checking experimental duration, level of experimental control, and type of reported data, i.e., C stocks rather than just carbon concentrations.

DATA AND METHODS

A literature survey of studies that aimed at comparing organic (ORG) versus conventional (CON) farming revealed a number of 39 experiments encompassing 68 datasets. Here, a dataset is defined as a combination of one pair of SOC contents, either concentration or mass, that either compares the state at a single point in time (ORG vs. CON; hereafter referred to as 'paired') or a comparison over time with known starting values for both, ORG and CON (hereafter referred to as 'controlled'). 'Experiment' refers to a comparison of organic versus conventional management at a given site. Numbers of datasets exceed those of experiments because i) time series conventional–conventional are not separately accounted for under experiments and ii) some studies include more than one fertilization level or stocking density.

A total number of 32 publications could be included in the survey. All studies appeared in peer-reviewed journals. They referred either to sites where conventionally managed land was converted to organic land and a conventional management control was maintained, or to paired plots where the time since conversion is documented, but differences between systems are reported only for the sampling date. In cases where more than one study reported SOC results from a particular experiment, we used the report covering the longest period, but included additional information concerning field activities from studies reporting on the same experiment but for shorter periods. Only studies were considered in which depth and time of soil sampling and experiment duration were equal for both organic and conventional management, and studies in which tillage differed between conventional and organic plots were excluded. Finally, information on crop rotation, fertilization (both organic and mineral fertilizer) was regarded essential.

While 'conventional farming' covers a wide range of possible farming practices, the term 'organic farming' is used for characterizing the implementation of a combination of various practices while other practices typical for conventional farming are excluded or prohibited by national or international regulations. With respect to SOM, regulations regarding fertilization, pest management, and diversity of crop rotations are of particular importance. Here we consider studies where organic farming is defined as a practice that excluded use of synthetic fertilizers and where no synthetic chemicals, e.g., pesticides, have been applied to the crop. In most studies, diverse crop rotations and application of organic fertilizers were characteristic for organic farming. We only considered studies where the conversion to organic farming dates back at least 3 years. These requirements were in agreement with general regulations and recommendations applied in most countries.

Some studies reported on biodynamic farming results. Biodynamic farming is based on the ideas of the Austrian anthroposophist Rudolf Steiner. As organic farming systems, biodynamic farming emphasises the use of manures and composts while it excludes the use of mineral fertilizers and synthetic chemicals. Methods unique to the biodynamic approach include the use of fermented herbal and mineral preparations as compost additives and field sprays, and the use of an astronomical sowing and planting calendar. In practice, in organic farming with biodynamic treatment manures are usually composted and are thus more stabilized than their counterparts.

To enable a comparison between different methods and periods of implementation, the change in SOC was captured as follows: For CON and ORG systems where initial SOC content has been measured, we use the relative rate of change as $(SOC_{t2} - SOC_{t1})$/experiment duration (years). An effect is expressed as percent change per year relative to the initial content, with the latter serving as the reference. For systems where initial conditions were not known (i.e., paired comparisons), we report $(SOC_{org} - SOC_{con})$/ experiment duration (years), assuming that both systems started from a similar baseline and that CON did not change over time. The effect is expressed as percentage change per year relative to SOC_{con}. These latter studies lack a true control and an effect is presented as percent change per year relative to the conventional treatment which is regarded as the reference. Negative numbers always denote C losses, positive numbers carbon gains.

We defined a range of criteria at the nominal scale to group results in order to evaluate the data sets:

Farming practices were divided into CON and ORG (see above) and 'DYN' when biodynamic farming was practiced. For most interpretation, DYN was considered a subset of ORG, but we discuss differences between ORG (non-dynamic) and DYN in a special section.

Data were further divided into the groups,

- reporting numbers relative to starting values (S) or relative to the conventional treatment (C) in paired designs
- reporting significant differences (yes, Y), no significant differences (no, N) or without reference to statistical indices (unknown, U) regarding SOC
- from replicated comparisons using a classical field experimental set-up (such as completely randomized factorial or split block designs) (denoted as plot, P) or using comparisons of fields or farms (denoted as farm, F, usually without replication or with pseudo-replication)
- having the same or similar crop rotations in CON and ORG (S), having different rotations (N) or insufficient information on rotation (unknown, U)
- providing measured SOC content on a concentration basis (C) or on a per-mass basis that includes bulk density measurements (M)
- with amounts of organic fertilizer applied in ORG higher (H), similar (S) or unknown (no information provided or information not clear; U) than in CON (Note: A category 'lower' had no hits). Experiments where both systems received no organic fertilization were classified as (S)
- where the amount of organic fertilizer or other organic additions to organic systems were supported by the systems productivity and crop rotation (proportional, P); exceeded the systems productivity or explicit reference is made to external inputs such as fish manure or seaweed, both regarded as external organic inputs (E). A third category (unknown, U) denotes data sets where the information was insufficient for classification.

Table 1 lists results of that classification for every single data set, sorted alphabetically by first author.

Statistics were calculated at the ratio scale for attributes sampling depth (cm), duration of the experiment (years), and relative change in SOC (% of reference). Means (±SE) of rates of SOC change are given throughout the text. Tabulated data also include median values and ranges for sampling depth and duration. 'Counts' (n) refers to number of data sets, not number of studies. Rates of SOC change were tested for significant differences from zero by a t test applying a 5% error probability.

RESULTS

General Results

The mean experimental duration was 17.6 years (CON 13.1, ORG controlled 15.0, ORG paired 21.1; Table 2). Across all data sets, the relative annual increase in SOC content was 1.68% (0.73). In CON, SOC changes by −0.16% (0.45) were not significant, whereas SOC in ORG significantly increased by 2.16% (0.90) on average. The increase was higher for controlled ORG trials (3.99 ± 2.35, n.s., $n = 20$) than for paired trials (1.08 ± 0.27, $P < 0.05$, $n = 34$) (Table 2).

Soils were sampled down to 20 cm on average, irrespective of management, with minimum and maximum depths of 7.5 and 50 cm, respectively. In 38 out of 68 data sets, samples were taken to a maximum of 20 cm, which roughly corresponds to the depth of the plow layer. In those studies, SOC increased significantly by 3.01% (±1.25), whereas in studies involving deeper layers a mean change by −0.01% (±0.25) was not significant.

Table 1 Overview of experiments, consulted references, classification of results, and supplementary information

References consulted for experiment	Experiment name	Duration	Management (a)	Percent change	Relative to conventional (C) or to start (S)	SOC difference significant: yes (Y), no (N), unknown (U)	Amount of manure in 'org' proportional to yields (P), external inputs (E), unknown (U)	Sampling depth (cm)	Same rotation yes (Y), no (N), unkown (U)	Data from repeated samplings yes (Y), no (N)	Applied amount of organic fertilizer in organic systems higher (H), lower (L), similar (S), unknown (U)	SOC measured as concentration (C) or mass (M)	Additional info
Results from plot experiments													
Clark et al. (1998)	SAFS	8	org	0.63	C	N	E	30	Y	N	H	C	
Drinkwater et al. (1998), Liebhardt et al. (1989), Wander et al. (1994), Pimentel et al. (2005)	Rodale	14	con	0.44	S	U		15	N	Y		M	Con 'referred' to as 'integrated' in paper
	Rodale	14	org	1.87	S	Y	U	15	N	Y	H	M	Bio with animals
	Rodale	14	org	1.18	S	Y	P	15	N	Y	S	M	Bio without animals
	Rodale	21	org	1.19	C	Y	U	30	N	N	H	M	Bio with animals
	Rodale	21	org	0.95	C	Y	P	30	N	N	S	M	Bio without animals
Eltun et al. (2002), Breland and Eltun (1999)	Kapp	7	con	−2.86	S	U		25	N	Y		C	Arable
	Kapp	7	org	−1.48	S	U	U	25	N	Y	H	C	Arable
	Kapp	7	con	−1.59	S	U		25	N	Y		C	Forage
	Kapp	7	org	−2.47	S	U	U	25	N	Y	H	C	Forage
Fließbach et al. (2007)	DOK	21	con	0.78	S	N		20	Y	Y		C	DOK: 'conventional' refers to integrated farming practice with manure in all cases
	DOK	21	org	0.80	S	N	P	20	Y	Y	S	C	All DOK data taken from Fließbach et al. refer to lower fertilization level
	DOK	21	dyn	0.70	S	N	P	20	Y	Y	S	C	
Friedel (2000)	Ensmad	21	org	0.53	C	N	U	25	Y	N	H	C	
Kirchmann et al. (2007)	Bärröd	19	con	−1.20	S	U		30	N	Y		C	
	Bärröd	19	org	−0.41	S	N	E	30	N	Y	S	C	
Kong et al. (2005, 2007), Denison et al. (2004)	LTRAS	10	con	−0.06	S	N		15	N	Y		M	
	LTRAS	10	org	3.26	S	Y	E	15	N	Y	H	M	

Table 1 continued

References consulted for experiment	Experiment name	Duration	Management (a)	Percent change	Relative to conventional (C) or to start (S)	SOC difference significant: yes (Y), no (N), unknown (U)	Amount of manure in 'org' proportional to yields (P), external inputs (E), unknown (U)	Sampling depth (cm)	Same rotation yes (Y), no (N), unkown (U)	Data from repeated samplings yes (Y), no (N)	Applied amount of organic fertilizer in organic systems higher (H), lower (L), similar (S), unknown (U)	SOC measured as concentration (C) or mass (M)	Additional info
Results from plot experiments													
Kramer et al. (2006), Reganold et al. (2001), Glover et al. (2000)	Washington state	9	org	5.83	C	U	E	7.5	Y	N	H	C	
Leifeld et al. (2009)	DOK	27	con	−0.48	S	Y		20	Y	Y		M	DOK: 'conventional' refers to integrated farming practice with manure in all cases
	DOK	27	org	−0.43	S	Y	P	20	Y	Y	S	M	All DOK data taken from Leifeld et al. refer to higher fertilization level
	DOK	27	dyn	−0.28	S	N	P	20	Y	Y	S	M	
Melero et al. (2006)	Andalusia	5	con	1.41	S	U		15	Y	Y		C	
	Andalusia	5	org	33.85	S	Y	E	15	Y	Y	H	C	
	Andalusia	6	con	4.06	S	U		15	Y	Y		C	
	Andalusia	6	org	30.13	S	Y	E	15	Y	Y	H	C	
Reeve et al. (2005)	McNab	6	org	−0.69	C	N	E	15	Y	N		C	
	McNab	6	dyn	−0.69	C	N	E	15	Y	N		C	
Robertson et al. (2000)	Michigan	10	con	0.00	S	N		7.5	N	Y		M	
	Michigan	10	org	0.85	S	N	P	7.5	N	Y	S	M	
Scheller and Raupp (2005), Raupp (2001)	Darmstadt 1998	18	con	−1.38	S	Y		25	Y	Y		C	Low
	Darmstadt 1998	18	org	−1.16	S	Y	P	25	Y	Y	H	C	Low; composted FYM without biodynamic prep. classified as 'org'
	Darmstadt 1998	18	dyn	−0.53	S	Y	P	25	Y	Y	H	C	Low
	Darmstadt 1998	18	con	−1.38	S	Y		25	Y	Y		C	Medium

Table 1 continued

References consulted for experiment	Experiment name	Duration	Management (a)	Percent change	Relative to conventional (C) or to start (S)	SOC difference significant: yes (Y), no (N), unknown (U)	Amount of manure in 'org' proportional to yields (P), external inputs (E), unknown (U)	Sampling depth (cm)	Same rotation yes (Y), no (N), unkown (U)	Data from repeated samplings yes (Y), no (N)	Applied amount of organic fertilizer in organic systems higher (H), lower (L), similar (S), unknown (U)	SOC measured as concentration (C) or mass (M)	Additional info
Results from plot experiments													
	Darmstadt 1998	18	org	−0.63	S	Y	P	25	Y	Y	H	C	Medium; composted FYM without biodynamic prep. classified as 'org'
	Darmstadt 1998	18	dyn	−0.32	S	Y	P	25	Y	Y	H	C	Medium
	Darmstadt 1998	18	con	−1.32	S	Y		25	Y	Y		C	High
	Darmstadt 1998	18	org	−0.74	S	Y	E	25	Y	Y	H	C	High; composted FYM without biodynamic prep. classified as 'org'
	Darmstadt 1998	18	dyn	0.11	S	Y	E	25	Y	Y	H	C	High
Wells et al. (2000)	New South Wales	3	con	−0.28	S	N		10	N	Y		C	
	New South Wales	3	dyn	18.49	S	Y	E	10	N	Y	H	C	

References consulted for experiment	Experiment name	Duration	Management (a)	Percent change	Relative to conventional (C) or to start (S)	SOC difference significant: yes (Y), no (N), unknown (U)	Amount of manure in 'org' proportional to yields (P), external inputs (E), unknown (U)	Sampling depth (cm)	Same rotation yes (Y), no (N), unkown (U)	Data from repeated samplings yes (Y), no (N)	Applied amount of organic fertilizer in organic systems higher (H), lower (L), similar (S), unknown (U)	SOC measured as concentration (C) or mass (M)	Additional info
Results from farm-scale experiments													
Blakemore (2000)	Haughtey	41	org	1.88	C	Y	P	25	Y	N	S	M	Change relative to con mixed
	Haughtey	41	org	2.02	C	Y	P	25	N	N	H	M	Change relative to con stockless
Gerhardt (1997)	Iowa	40	org	5.14	C	Y	U	10	N	N	H	C	
	Iowa	40	org	−0.30	C	N	U	40	N	N	H	M	

Table 1 continued

References consulted for experiment	Experiment name	Duration	Management (a)	Percent change	Relative to conventional (C) or to start (S)	SOC difference significant: yes (Y), no (N), unknown (U)	Amount of manure in 'org' proportional to yields (P), external inputs (E), unknown (U)	Sampling depth (cm)	Same rotation yes (Y), no (N), unkown (U)	Data from repeated samplings yes (Y), no (N)	Applied amount of organic fertilizer in organic systems higher (H), lower (L), similar (S), unknown (U)	SOC measured as concentration (C) or mass (M)	Additional info
Results from farm-scale experiments													
Liebig and Doran (1999)	Nebraska, North Dakota	9	org	0.46	C	N	U	30.5	N	N	H	M	
	Nebraska, North Dakota	29	org	1.25	C	Y	P	30.5	N	N	S	M	
	Nebraska, North Dakota	10	org	2.64	C	Y	U	30.5	N	N	U	M	
	Nebraska, North Dakota	19	org	1.87	C	Y	U	30.5	N	N	H	M	
	Nebraska, North Dakota	19	org	0.69	C	N	U	30.5	N	N	H	M	
Marinari et al. (2006)	Colle Valle Agrinatura	7	org	−0.61	C	N	U	35	N	N	H	C	
Nguyen et al. (1995)	Canterbury	8	dyn	0.00	C	U	U	7.5	N	N	H	C	Kowai crop phase
	Canterbury	8	dyn	1.52	C	U	U	7.5	N	N	H	C	Kowai pasture phase
	Canterbury	8	org	−0.39	C	U	U	7.5	N	N	H	C	Temuka crop phase
	Canterbury	8	org	0.39	C	U	U	7.5	N	N	H	C	Temika pasture phase
	Canterbury	8	org	0.46	C	U	U	7.5	N	N	S	C	Templeton crop phase
	Canterbury	8	org	0.43	C	U	U	7.5	N	N	S	C	Templeton pasture phase
Pulleman et al. (2003), Droogers and Bouma (1996)	Polder	70	dyn	0.80	C	Y	E	20	Y	N	H	C	Arable
	Polder	70	dyn	0.03	C	Y	E	50	U	N	H	M	Arable
	Polder	70	dyn	0.67	C	N	E	50	U	N	H	M	Ley

Table 1 continued

References consulted for experiment	Experiment name	Duration	Management (a)	Percent change	Relative to conventional (C) or to start (S)	SOC difference significant: yes (Y), no (N), unknown (U)	Amount of manure in 'org' proportional to yields (P), external inputs (E), unknown (U)	Sampling depth (cm)	Same rotation yes (Y), no (N), unkown (U)	Data from repeated samplings yes (Y), no (N)	Applied amount of organic fertilizer in organic systems higher (H), lower (L), similar (S), unknown (U)	SOC measured as concentration (C) or mass (M)	Additional info
Results from farm-scale experiments													
Reganold et al. (1993)	New Zealand North Island	12	dyn	3.38	C	Y	U	10	Y	N	H	C	
	New Zealand North Island	15	dyn	1.63	C	Y	E	10	Y	N	H	C	
	New Zealand North Island	8	dyn	2.02	C	Y	E	10	Y	N	H	C	
	New Zealand North Island	10	dyn	−2.05	C	N	E	10	Y	N	H	C	
	New Zealand North Island	13	dyn	2.16	C	Y	E	10	Y	N	U	C	
	New Zealand North Island	24	dyn	−0.42	C	N	E	10	Y	N	H	C	
	New Zealand North Island	25	dyn	0.79	C	Y	U	10	Y	N	S	C	
Stamatiadis et al. (1996)	Aegion	4	org	2.46	C	N	E	15	Y	N	H	M	
Results from plot experiments													

Table 2 Overview of key data for the comparison of organic versus conventional farming including relative SOC change rates per year

Experiment setup (from-to)[a]		Duration (years)[d]	Depth (cm)[e]	Annual change[f] (percent)					N[h]
				Total	Experiment type[g]		SOC measure		
					Plot	Farm	Concentration	Mass	
con–con		12, 13.1	20, 20	−0.16	−0.16	–	−0.21	−0.03	14
		(3–27)	(7.5–30)	(0.45)	(0.45)		(0.64)	(0.19)	
con–org	start[b]	18, 15.0	20, 20	3.99	3.99	–	5.24	1.07	20
		(3–27)	(7.5–30)	(2.35)	(2.35)		(3.33)	(0.56)	
	con[c]	12.5, 21.1	15, 20	1.08	1.11	1.07	0.93	1.34	34
		(4–70)	(7.5–50)	(0.27)	(0.84)	(0.28)	(0.40)	(0.24)	

[a] con–con continuous conventional management with SOC measured initially, con–org change from conventional to organic practice with either (b) change rate is calculated relative to initial value or (c) change rate between organic and conventional farming is based on paired plots without reference to initial conditions

[b] Relative to starting value

[c] Relative to conventional system at time of sampling

[d] Median, mean (min and max)

[e] Median, mean (min and max)

[f] Mean carbon change rate per year (percentage of reference) relative to starting value or conventional control, 1 SE in parenthesis

[g] *Plot* controlled field experiment, *Farm* comparison of adjacent farms

[h] Number of data sets for three experimental set-ups

Forty-six out of 68 data sets reported SOC concentration, and only 22 SOC mass per unit area. When C concentrations were reported, SOC changed by −0.22% (±0.64, $n = 10$) for CON and by 2.61% (±1.34, $n = 36$) for ORG. Changes in studies reporting C mass were −0.03% (±0.19, $n = 4$) for CON and 1.25% (±0.24, $n = 18$) for ORG. Only the latter change was significantly different from zero.

The change in SOC was on average higher (3.30% ± 1.58) for short-term (up to 10 years) than for long-term experiments (0.40% ± 2.20; Fig. 1). However, this holds true only when three data sets with fast rates of SOC change were included (crosses at $t = 3, 5, 6$ years). When excluding these three results, the mean rate of change was similar in short-term and long-term experiments (0.61% ± 0.36). The increase in SOC in these three examples (Wells et al. 2000; Melero et al. 2006) was due to exceptionally high rates of compost application.

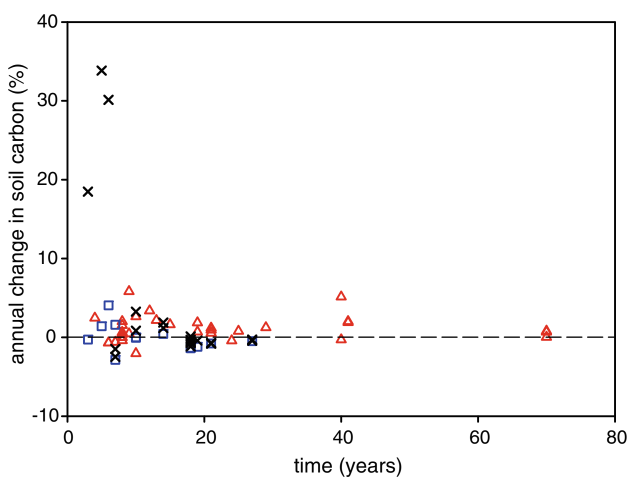

Fig. 1 Soil carbon change rate as a function of experimental duration. *Triangles*: organic farming relative to conventional (paired comparisons). *Squares*: conventional farming relative to experimental start. *Crosses*: organic farming relative to experimental start

Significance of Differences

Most studies reported a significant increase in SOC content for ORG (4.03 ± 1.64; $n = 28$), but significant negative trends in CON (−1.14 ± 0.22, $n = 4$). Less studies found a non-significant decline in ORG ($n = 17$) and CON ($n = 4$), or differences in SOC were not analyzed statistically ($n = 15$).

Plot Versus Farm Scale

Half of the 54 ORG data sets were derived from plot experiments where SOC increased non-significantly by 3.24% (±1.76) per year. The same number of data sets but from farm-scale comparisons showed an increase in SOC by 1.07% (±0.28, $P < 0.05$). Twenty ORG data from plot trials provided initial conditions; they changed non-significantly by 3.99% (±2.35). Only seven data sets at the plot scale reported paired comparisons. There was a high agreement between the metrics controlled/paired on the one hand and plot/farm scale on the other.

Crop Rotation

Changes in SOC in ORG systems with crop rotations similar to those in CON were not significant (2.84 ± 1.65, $n = 27$). For ORG systems with rotations different from CON, the change was only 1.56% (0.77, $n = 25$, n.s.). Corresponding changes in CON were zero and −0.33% (±0.53), respectively.

Organic Fertilization

Where the amount of organic fertilizer in ORG exceeded that applied in CON, the annual increase in SOC was 2.91% (±1.29, $P < 0.05$; $n = 37$). In contrast, SOC changes in ORG were not significant (0.40 ± 0.24, $n = 13$) for trials where the amount of organic fertilizer was similar to CON. In 20 cases, we considered the amount of organic fertilizer applied to ORG to exceed the systems' productivity. Here, SOC increased significantly by 4.85% (±2.29; $P < 0.05$; $n = 20$). When organic fertilizer was applied according to the systems' productivity, changes were only 0.23% (±0.29, $n = 14$, n.s.). In 20 cases we could not resolve whether organic fertilization was proportional to productivity or externally driven. Restricting the analysis to the 14 experiments where initial conditions in CON and ORG were known, SOC in systems with similar applications of organic fertilizer in both CON and ORG did not change significantly (ORG: 0.05% ± 0.28; CON: −0.16% ± 0.45). Only four organic data sets met the requirement of having known starting conditions, application rates of organic fertilizers proportional to the systems' capacity, and the same crop rotation as CON. They lost SOC on average by −0.55% (0.12), whereas similar ORG systems but receiving fertilizer inputs exceeding the systems' productivity gained SOC on average by 15.84% (9.35; $n = 4$).

Biodynamic Farming

Three experiments comprising six datasets compared ORG and DYN plots (Raupp 2001; Reeve et al. 2005; Fließbach et al. 2007; Leifeld et al. 2009). Among these, ORG lost −0.74% (±0.10) whereas biodynamic systems lost only 0.40% (±0.13). The difference between those numbers turned out to be significant ($P < 0.05$) when using a two-tailed, paired t test.

DISCUSSION

Factors Causing Differences in SOC

This analysis reveals that in terms of soil C sequestration, ORG but not CON has a positive effect and leads to a significant increase in SOC, i.e., the relative rate of the change in SOC is >0. However, the difference between ORG and CON across the data set is not significant. The same result appears when the analysis is limited to studies with known initial conditions, which are considered more meaningful.

An increase in SOC can be attributed to several factors, with the input of organic fertilizers as the single most important driver. Typically, ORG received higher rates of organic fertilizer than CON, where often only mineral fertilizer was applied. However, the difference between ORG and CON was reduced when organic fertilizers were applied at similar rates in ORG and in CON. This confirms the well-known relationship between the amount of organic fertilizer input and SOC content, which is independent of the type of management (e.g., Jenkinson 1991; Buyanovsky and Wagner 1998; Blair et al. 2006). It should be noted that in many cases ($n = 16$) in which fertilizer application rates in ORG exceeded those in CON, the fertilizer originated from outside the system and the amount did not match the systems' productivity. In these ORG systems, SOC increases significantly by +6.04% (±2.80). In contrast, in ORG systems fertilized according to the systems' productivity (including the category 'unknown'), but with higher amounts than in CON, SOC did not change significantly. The results thus confirm that the benefit of ORG for SOC is largely determined by a higher and often disproportionate application of organic fertilizer.

In more closed systems not importing manure it is likely that the benefit of organic fertilization is smaller. Application of manure produced within the system, for example, does not add additional C to the system (see, e.g., Schlesinger 2000). Conversely, CON systems including grass-clover mixtures or other forages in rotation produce similar amounts of manure, but if this manure is not returned to the field, the true C balance of such a system can only be quantified when sequestration off-site is considered. This limits the diagnostic value of controlled experiments when C budgets are restricted to the scale of individual plots or fields. Besides input rates, qualities of organic fertilizers may differ among systems. Composted manure is typical for DYN, and, given that composting stabilizes organic matter such as raw manure, nominal equal C inputs may have differential effects on SOC. For the DOK experiment a loss of 21% C for 'conventional' manure versus 39% for composted manure prior to field application has been estimated (Leifeld et al. 2009). Thus, the actual field balance without considering CO_2 produced off-site becomes biased.

In farm-scale comparisons, SOC increased significantly in ORG but not under controlled conditions. Thus, if farm-scale comparisons were excluded from the analysis, the above positive effect of ORG on C sequestration diminishes. Farm-scale comparisons typically miss true replicates and are thus less meaningful than controlled experiments. Unexpectedly, experimental duration had no effect on the rate of change when three extreme values were eliminated, possibly because the overall rates of change were small. However, that finding must not be overemphasized given that in our kind of meta-analysis data sets of various origins are lumped together. According to the general perception of SOC dynamics as represented in dynamic SOC turnover models, change rates are faster shortly after management changes. This is because short-lived soil C pools respond quickly to changing environmental conditions (e.g., Collins et al. 2000).

Diverse crop rotations including legumes, which are typical for organic farming, should have a measurable effect on SOC, a suggested by a review by Jarecki and Lal (2003). In this study, where ‘different rotation’ always meant a higher diversity in ORG, differences between crop rotations appeared to be a factor of minor importance for the rate of SOC change. These rates in CON and ORG were not significantly different, and SOC in ORG with crop rotations similar to those in CON changed even less. This is in contrast to the idea that typical ‘organic rotations’ promote C sequestration. However, we attribute the lack of statistical significance to the high variability of change rates, and to the dominant effect of organic fertilization. In individual experiments, as for example the long-term trial in Rodale, Pennsylvania (Pimentel et al. 2005), the organic stockless rotation included hairy vetch and red clover in combination with maize and soybean whereas CON had only maize and soybean. Though organic fertilizer was neither applied to ORG stockless nor to CON, SOC increased more in ORG, thereby supporting the view of diverse rotations to be more beneficial to SOC, most likely due to higher input rates and longer periods of soil coverage.

A small number of data suggest that biodynamic farming protects against SOC losses more effectively than organic farming without biodynamic practices. In a paired *t* test, the difference in SOC content between DYN and ORG was significant. Only one experiment in a Californian vineyard showed no difference in SOC between ORG and DYN (Reeve et al. 2005),whereas systematic differences were found in two controlled, long-term experiments at temperate sites in Germany (Raupp 2001) and Switzerland (Fließbach et al. 2007, for lower fertilization level, and Leifeld et al. 2009, for higher fertilization level). In the study of Raupp (2001), loss of SOC relative to CON was smaller in DYN than in ORG for low- and medium-level manure application and DYN was the only system that gained SOC under high organic fertilization. In this experiment, fertilization levels were the same for CON, ORG, and DYN, and fertilization was normalized to the same amount of nitrogen input (total nitrogen). Actual dry matter applications of organic fertilizer were not reported but were probably similar in both ORG and DYN given that manure in both systems was composted and most likely had a similar C/N ratio. The non-composted manure in CON may have had a wider C/N ratio and thus may have been applied at higher rates. While the German study may indicate a differential effect of DYN on SOC it must be noted that bulk densities were not reported, only topsoil was considered and a single SOC was given as starting value for all the plots. The DOK trial in Switzerland also showed systematic, albeit often non-significant effects, of DYN relative to ORG. In contrast to Raupp (2001), the pretreatment of manure differed between ORG (matured manure) and DYN (composted manure). In a recent publication on that experiment, Leifeld et al. (2009) argued that differences between the different organic systems were mostly due to differences in initial SOC and not due to the practice itself. Together, at current there is no unequivocal evidence for a positive effect of DYN on SOC stocks relative to ORG, and thus more research with properly designed and documented experiments is needed.

Experimental Limitations

Apart from differences in management practices that are not unique to organic farming, many studies suffered from shortcomings that reduce their scientific value. Most important limitations are (i) unknown starting conditions (i.e., the study was not controlled) and (ii) reporting of C concentrations rather than C masses. Unknown starting conditions make it impossible to assign differences in SOC between treatments to management itself, and even well-controlled studies may suffer from initial differences between plots that interfere with treatment effects (Leifeld et al. 2009). In the majority of the data sets, C concentrations rather than C mass is given, which strongly limits interpretation of SOC changes as changes in concentration may go along with changes in bulk density. Ideally, not only the same volumes but equivalent soil masses should be sampled when examining the effect of a specific practice on SOC (Ellert and Bettany 1995). The fact that in ORG changes were more than twice when only concentrations were reported stresses the need to report also bulk densities.

We also consider the duration of many experiments as too short. In 30 out of 68 the duration was 10 years or less. Long-term agricultural studies indicate that the rate of change in SOC may be greatest at the beginning of the experiment but that reaching a new steady-state may take more than 100 years (Johnston et al. 2009). Our analysis shows that a single application of organic fertilizer causes a bias toward increasing SOC during the first years. Also, sampling depth is often too limited to draw firm conclusions about the effect of management on SOC stocks. In 38 out of 68 samplings sampling depth was 20 cm or less. In these studies response of SOC was significantly different from studies that included subsoil. While SOM is more dynamic in the topsoil, also subsoil OM is actively involved in C cycling (Baisden and Parfitt 2007; Don et al. 2009). Neglecting deeper soil C dynamics could lead to misinterpretation of management effects as the subsoil SOC trend may be opposite to that observed in the topsoil (Baker et al. 2007).

In spite of their limitations with respect to the analysis of long-term SOC dynamics, the comparative experiments still have their value, as their main emphasis often was on parameters other than changes in SOC and sampling was designed accordingly. For instance, this is the case for microbial or enzymatic activities which can be normalized to SOC or OM concentrations. In controlled experiments, different crop rotations can be installed and compared, which are representative for conventional and organic systems, as in the case of the Rodale experiment (e.g., Pimentel et al. 2005). Comparisons at the farm level may search for general patterns of organic farming systems (e.g., Liebig and Doran 1999), and studies may have to rely on non-controlled paired comparisons because of unique experimental features (e.g., a biodynamic farm on a Dutch Polder established 70 years ago, Pulleman et al. 2003).

An 'ideal' experiment should (i) be controlled, (ii) last more than 20 years, (iii) consider both topsoil and subsoil, (iv) measure C mass, and (v) have comparable management in terms of organic fertilization and crop rotation. In the available reports, none of the studies meets this combination of requirements. If we exclude the subsoil criterion, there is one study with two ORG systems (ORG and DYN) that meets the rests of the criteria. In this single case, a significant loss of SOC over 27 was reported for ORG, whereas for DYN systematic differences in soil properties (texture, pH, more SOC at beginning of experiment) caused the decline to be smaller and non-significant (Leifeld et al. 2009). For an improved mechanistic understanding, an ideal experiment should also allow to quantify all inputs into soil including inputs by roots and rhizosphere as, for example, root-to-shoot ratios may depend on nutrient availability (Wilts et al. 2004).

Management and Greenhouse Gases in Agriculture

The data included here suggest that the benefit of organic versus conventional management for SOC stocks is mainly due to the higher and often disproportionate application of organic fertilizer. In practice, many conventional systems are highly specialized stockless systems that produce no manure, while highly intensive cattle farms or grazing-based dairy systems produce an excess of manure or slurry. As accrued manure may not be applied at optimum rates in conventional farms, C balance calculations of conventional agriculture need to account for all land, i.e., cropland, grassland, and mixed rotations. The selective reporting of results from CON that received no manure leads to a biased estimate for that system.

It has been argued that applying manure on cropland rather than on grassland may increase SOC more because croplands are considered to be more deficient in SOC (Smith et al. 2001). However, there is strong indication that even in the case of SOM-rich permanent grasslands or pastures manure application increases SOC (Jones et al. 2006; Olson and Papworth 2006; Dijkstra et al. 2006) and that SOC saturation levels, as proposed by Stewart et al. (2007), do not exist, or have not been reached yet. Together, there is evidence that the overall C balance of soil, provided similar amounts of manure are available, is not systematically different between, on the one hand, mixed (organic) systems where manure is applied within single farms or, on the other hand, specialized conventional farming that selectively spreads high rates of manure but only on a fraction of the conventional land. But it should be noted that excessive organic fertilization, be it in conventional or organic systems, may cause substantial environmental problems, for example nutrient leaching (Bergström et al. 2008), which needs to be tackled by sustainable management practices.

The view of the global warming fingerprint of any farming system cannot be limited to changes in SOC, and C sequestration is just one of many environmental factors, which needs to be accounted for. Intimately related to SOC are other aspects of a farm's greenhouse gas (GHG) balance. In this respect emissions of nitrous oxide and methane, two other important long-lived greenhouse gases that are emitted or taken up by biological processes in agriculture, are particularly relevant. Globally, agriculture contributes 10–12% of the total anthropogenic GHG emissions, or about 5.1–6.8 Gt of CO_2 equivalents per year, most of it as CH_4 and N_2O (UNFCCC 2008). For example, these two gases accounted for about 3.3 and 2.8 Gt CO_2 equivalents in 2005. It has been argued that most of the agriculturally derived GHG emissions can be compensated for by soil C sequestration (UNFCCC 2008). Full GHG budgets of organic and conventional farming demonstrated the effect of management on N_2O and CH_4 emissions, but differences between systems were most pronounced for the rate of soil C uptake or loss, i.e., soil C was the single most important factor in the overall balance of biologically mediated GHG processes (i.e., excluding fossil fuels, liming, etc; Robertson et al. 2000). These findings stress, in line with our analysis, the need for more comprehensive in-depth studies on the effect of organic farming on SOC.

Niggli et al. (2009) regarded C sequestration as the single most important measure for low GHG organic agriculture. They argued that in the context of climate change and livestock production, a per area calculation of GHG emissions would be more appropriate than a per product quantity for farming system comparisons. According to lifecycle assessments at the farm scale, organic farming systems perform better in terms of climate impact when calculated on an area-related basis, but are similar to conventional systems when emissions are related to production (Flessa et al. 2002; Haas et al. 2001) due to the often lower yields in organic agriculture. We argue that the supply of high-quality food and fiber is a key purpose of agriculture for any production system and that the amount of food produced should set the scale for system analysis. Finally, how much of the presumed environmental benefits of organic farming are offset by a higher demand for land due to lower yields is a matter of debate (Andrén et al. 2008; Ewers et al. 2009) and needs further analysis.

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