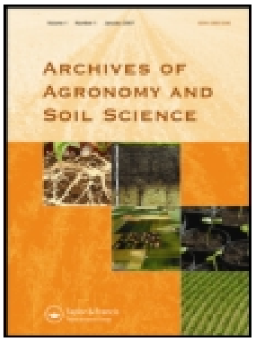

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Effect of mineral and organic fertilization on crop yield, nitrogen uptake, carbon and nitrogen balances, as well as soil organic carbon content and dynamics: results from 20 European long-term field experiments of the twenty-first century

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Assembled results from 20 European long-term experiments (LTE), mainly from the first decade of the twenty-first century, are presented. The included LTEs from 17 sites are the responsibility of institutional members of the International Working Group of Long-term Experiments in the IUSS. Between the sites, average annual temperatures differ between 8.1 and 15.3°C, annual precipitation between 450 and 1400 mm, and soil clay contents between 3 and 31%. On average of 350 yield comparisons, combined mineral and organic fertilization resulted in a 6% yield benefit compared with mineral fertilization alone; in the case of winter wheat, the smallest effect was 3%, the largest effect, seen with potatoes, was 9%. All unfertilized treatments are depleted in soil organic carbon (SOC), varying between 0.36 and 2.06% SOC. The differences in SOC in unfertilized plots compared with the respective plots with combined mineral (NPK) and organic (10 t ha^{-1} farmyard manure) fertilization range between 0.11 and 0.72%, with an average of 0.3% (corresponding to ∼15 t ha^{-1}). Consequently, the use of arable soils for carbon sequestration is limited and of low relevance and merely depleted soils can temporarily accumulate carbon up to their optimum C content.

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†Zoran Čergan died in 2012.

Keywords: long-term experiments; crop yields; nitrogen uptake; soil organic carbon; carbon and nitrogen balances

Introduction

Long-term experiments are essential in agricultural, nutritional and environmental research (Körschens 2006). The wide variety of soil, climatic and weather conditions, as well as the huge variability in important soil properties over space and time, demand a comprehensive experimental basis at many sites and over many decades.

In fact, there are ~80 European long-term experiments (LTEs) of more than 20 years duration being undertaken by research institution members of the International Working Group of Long-term Experiments (IOSDV/LTE) within the International Union of Soil Science (IUSS). Fifty of these experiments have run for more than 40 years, and two of them have run for more than 100 years (Appendix 1 and 2). These LTEs represent different soil types and climates. Worldwide, ~600 LTEs (Debreczeni and Körschens 2003) cover essential topics and research questions that can be solved only by long-term experiments, for example:

- the effect of fertilization and management on yield, soil fertility, food quality, pests and pathogens;
- the quantification of trace gas emissions;
- the development of humus balance methods;
- soil carbon and nitrogen dynamics;
- soils as carbon sinks and sources;
- interactions between climate, soil and plant;
- deducing optimal soil carbon contents; and
- verification of models for applied and environmental research.

Within the last decades of the 20th century, results from LTEs were used to quantify soil C and N dynamics, and develop methods for achieving humus balance.

Over time, yields increased substantially, and so too have the amount of harvesting and root residues remaining on the field; simultaneously, over the last 50 years, average annual temperature has increased by 1.0–1.5°C. There is, therefore, a need to analyse recent results in light of actual and expected future conditions.

Materials and methods

The experiments included in this analysis are detailed below.

- The series of 'International Long-term Organic Nitrogen Fertilization Experiments' (IOSDV), started during 1984 and 1992 on the initiative of Professor von Boguslawski (Appendix 2).
- Three LTEs of the series L 28 (Bad Salzungen, Methau and Spröda, see Table 1) started in 1966 (Ansorge and Pößneck 1992; Albert 2001, 2011; Albert and Lippold 2002).
- Long-term fertilization experiment with different organic fertilizers and graduated mineral N fertilization at Müncheberg (Germany).
- 'Classic' long-term field experiments, such as:

- Static Fertilization Experiment Bad Lauchstädt (started 1902) (Körschens and Pfefferkorn 1998);
- long-term organic fertilization experiment – F field – Halle (started 1948) (Merbach and Deubel 2007);
- LTEs at Thyrow (Ellmer and Baumecker 2005); and
- long-term experiments in Spain, Czech Republic and Hungary (Kubát et al. 2003, 2006; López-Fando et al. 2007; Kismányoky 2009; López-Fando and Pardo 2009).

With the exception of the Static Fertilization Experiment Bad Lauchstädt, in the IOSDV experiments in Slovenia and Rauischholzhausen all crops of a rotation grown side by side every year, in all other experiments each crop grows only once in a rotation.

Here, we present results mainly from the first decade of the 21st century relating to 20 LTEs from 17 sites (Table 1). These sites represent the range of climates between the north of Germany and Spain, with average annual temperatures between 8.1 and 15.3°C, annual precipitation between 450 and 1400 mm, and soils containing 3–31% clay. The individual results of selected experiments will be presented separately.

Results and discussion

Yields

During the last 50 years, crop yields both in field experiments and on farmland, especially for cereals, have more than doubled as a consequence of successes in plant breeding, the application of plant-protecting and growth-regulating chemicals, and the better adaptation of fertilization regimes. As an example, at Chernozem, Bad Lauchstädt, winter wheat yields in the Static Fertilization Experiment increased by only 1 up to 5 t ha^{-1} between the beginning of the twentieth century and 1970; but in the four decades since 1970, have yields increased to >9 t ha^{-1}. Compared with these figures, winter wheat yields at Broadbalk Field, Rothamsted stagnated over a period of 120 experimental years from 1850 to 1970 at 4 t ha^{-1}; thereafter yields increased to 9 t ha^{-1} (Goulding and Poulton 2002).

Under German farm conditions, similar trends in yield were found. Up to 1960, average winter wheat yields remained below 3 t ha^{-1}, increasing over the decades since 1960 to 7.5 t ha^{-1} (Author Team 2008); however, yields have stagnated over the last 10–15 years. In addition to yield, the amount of harvesting and root residues has also increased. A grain yield of 1 t ha^{-1} corresponds, on average, to a harvesting and root residue of 0.2 t ha^{-1} (Körschens 2010).

Long-term field experiments allow us to study the impact of fertilization and/or soil organic matter (SOM) on crop yield, which is of particular importance. A broad analysis of LTEs over recent decades showed that the soil improving effect of SOM led to a yield increase of up to 10% on sandy soils and up to 6% on loamy soils (Scholz 1978). More recent investigations confirm this (Beuke 2006).

Taking the results of 16 LTEs, covering 246 (Table 2) and 350 experimental years, when considering all the crops in a rotation, the yield increase for combined organic and mineral fertilization was 6% compared with optimal mineral fertilization alone. The lowest effect (3%) was estimated for winter wheat (n = 92) and the largest effect (9%) for potatoes (n = 40). Crops of fewer than three

Table 1. Country and location of different long-term experiments.

Country	Experimental objective	Initial year	Soil texture	Clay content (%)	Mean annual temperature (°C)	Mean annual precipitation (mm)
Austria						
Wien	IOSDV	1986	loamy sand	25	9.4	529
Czech Republic						
Prague	organic + mineral fertilization	1955	loam	31	8.1	450
Germany						
Bad Lauchstädt	Stat. Fertiliz. Experiment	1902	loam	21	8.8	489
Bad Salzungen	L28 organic + mineral fertilization	1966	loamy sand	8	8.1	568
Berlin-Dahlem	D III; diff. management	1923	sand	4.3	9.3	550
	IOSDV	1984	sand	4.3	9.3	550
Großbeeren	Box Plot Experiment	1972	silty sand	6	8.4	527
			silty loam	17		
			clayey loam	28		
Halle	Field F, FYM + min-N	1949	sandy loam	12	9.2	494
Methau	L28, organic + mineral fertilization	1966	loam	15	8.2	680
Müncheberg	organic + mineral fertilization	1963	loamy sand	5	8.7	546
Rauisch-holzhausen	IOSDV	1984	loam	17	8	583
Speyer	IOSDV	1983	loamy sand	9	10	600
Spröda	L28, organic + mineral fertilization	1966	loamy sand	6	8.9	465
Thyrow	Nutrient depletion exp.	1937	sand	3	8.6	520
	Soil fertility exp.	1938	sand	3	8.6	520
Hungary						
Keszthely	IOSDV	1984	loam	21	10.8	547
	organic + mineral fertilization	1967	loam	21	10.8	547
Slovenia						
Jable	IOSDV	1992	loamy silt	17	9.7	1397
Rakican	IOSDV	1992	loamy sand	15	9.4	810
Spain						
Madrid	IOSDV	1984	loamy clay	27	15.3	489

Note: IOSDV, International Organic Nitrogen Long-term Fertilization experiment.

Table 2. Comparison of yields of exclusive mineral fertilization (= 100) and of combined organic and mineral fertilization; results from 15 European long-term experiments.

				Relative yield (combined organic and mineral fertilization via mineral fertilization [100])								
Country	Initial year	Evaluation period		Winter wheat	Winter barley	Spring barley	Oats, spring wheat	Sugar beets	Sugar	Potatoes	Corn	Sorghum, rye
Austria												
Wien	1986	1995–2006	12	101	106	–	–	110	103	–	–	–
Germany												
Bad Lauchstädt	1902	2001–2010	10	104	–	105	–	107	–	114	–	–
Bad Salzungen	1966	1993–2010	18	106	109	108	108[a]	–	–	115	111	–
Berlin-Dahlem	1984	1999–2010	12	103	–	104	–	–	–	109	–	–
Halle/Saale	1948	1950–2010	61	95	–	104	110[a]	101	–	110	104	–
Methau	1966	1999–2010	12	105	–	107	–	–	102	131	–	–
Müncheberg	1963	1982–2004	23	100	–	108	–	102	–	100	–	102 rye
Rauisch-holzhausen	1984	1999–2008	10	106	98	–	–	109	–	–	–	–
Speyer	1984	2001–2010	10	102	103	–	–	113	110	–	–	–
Spröda	1966	1999–2010	12	98	–	98	–	–	112	92	–	–
Thyrow[b]	1937	1998–2010	13	–	–	–	–	–	–	–	119	107 rye
Hungary												
Keszthely	1984	2000–2010	11	109	109	–	–	–	–	–	106	–
	1967	2001–2010	10	97	–	–	–	–	–	106	97	–
Slovenia												
Rakican	1992	2001–2010	10	95	112	–	–	–	–	–	110	–
Jable	1992	2001–2010	10	100	–	–	97	–	–	–	100	–
Spain												
Madrid	1984	2000–2011	12	111	–	102	–	–	–	–	–	106
n[c]			246[d]	92	39	43	22	42	6	40	52	14

Notes: [a]Spring wheat, [b]soil fertility experiment, [c]number of LTE years per crop, [d]number of total LTE years.

treatment comparisons were not considered. Although a yield range of 95–112% for all cereals was rather small, larger variations in yield of 92–131% were recorded for potatoes; however, the value of 131% at Methau is presumably an outlier. In general, no differentiation between sites can be derived from the results.

With the exception of the Static Fertilization Experiment Bad Lauchstädt, where graduated farmyard manure (FYM) fertilization is also included, all other experiments are laid out with or without FYM only, and with graduated nitrogen fertilization beyond optimum doses.

An increase in the amount of FYM applied from 10 to 15 t ha^{-1} a^{-1} had no significant effect on yield in the Static Fertilization Experiment Bad Lauchstädt; on average, for the crop rotation (40 comparisons), a 5 t ha^{-1} a^{-1} increase in FYM gave equivalent yields (99%), which corresponds to results for the period 1991–2000 (Rathke et al. 2002). Only in two years was there a yield increase, of 6% for maize, due to an increase in the amount of FYM applied in the LTE at Müncheberg (18 comparisons), but on average for all crops, no effect (99% yield) was measured. This confirmed previous results (Author Team 2004) which showed a yield and nutrient utilization-oriented optimal FYM amount of 10 t ha^{-1} a^{-1} for a wide range of sites. This allows us to conclude that overall carbon turnover at the different sites is equivalent, varying only in terms of the proportions of SOM and primary organic matter (POM). For the crop rotation winter wheat–sugar beet–spring barley–potato, and a fertilizer application of 10 t FYM ha^{-1} a^{-1} + NPK at two sites, Spröda and Bad Lauchstädt, it can be assumed that under steady-state conditions, annual C turnover is equivalent (Spröda: SOC 0.83%, SOC difference between 'without fertilization' and optimal fertilization 0.15%; Bad Lauchstädt: SOC = 2.06%, SOC difference between 'without fertilization' and optimal fertilization = 0.72%).

The average yield of winter wheat varies between sites, from 4.8 to 9.4 t ha^{-1}; single maximum yields of 11.8 t ha^{-1} were obtained at Bad Lauchstädt and similar yields of 11.3 t ha^{-1} were obtained for German farms in 2010.

SOC content in top soil, C dynamics and C balance

Because of the wide variability in SOC over space and time, significant changes can only be proved by recurrent analyses over long periods. For detailed predictions, comparisons of SOC on the basis of only two analyses within a short time span are inapplicable. It is also doubtful whether the decades before the start of the experiments can be compared without further analyses over the experimental period. Methodical differences in sampling, sample preparation, uncertainties in calculating carbon stocks with regard to different tilling depths and bulk densities, and the analysis used may have a considerable affect on results and trends. Moreover, the SOC and N contents before the start of an experiment are of crucial importance. As an example, the SOC content of a soil with a high SOM supply due to previous management techniques may decrease until a new level is reached; even if fertilization is adapted according to an equal humus balance. This was found in the experiments at Methau and Spröda. In all treatments, SOC content decreased considerably during the first 20 years of the experiment; at Spröda with optimal FYM application, the decrease was by at least 0.5% SOC (Albert Forthcoming 2012). Similar results were found at Halle/Saale; here, the SOC content of the top soil in all treatments has decreased by 0.5% over the last 30 years due to changes in environmental conditions (e.g. reduced C immissions) and a deepening of the top (tilled) soil (Merbach and Deubel 2007).

The starting SOC value for the IOSDV experiment at Speyer was already optimal; even in the FYM + NPK treatment this value remained unchanged over 25 experimental years. Likewise, SOC content in the experiment at Vienna had not changed significantly after 21 experimental years (Spiegel et al. 2010).

Comparable results were found in the Box Plot Experiment Großbeeren (Rühlmann 2003) where the effects of different fertilization treatments were tested using three soil types under the same weather conditions. Compared with the other soil types, the SOC content in a sandy soil with 5.5% clay remained almost unchanged in the unfertilized treatment and showed the smallest increase in the NPK and NPK + FYM treatments (Figure 1). The SOC contents in soils with 27.5 and 17.5% clay showed increases of a comparable magnitude in the treatment without fertilization and the treatments with mineral and mineral + organic fertilization. The results show that the direction of the trend in SOC can hardly be used as a decision criterion, unless the starting level is known and can be appropriately classified. As an example, the extension of the Static Fertilization Experiment Bad Lauchstädt in 1978 (Körschens and Pfefferkorn 1998) should be mentioned. At this time, after 75 experimental years, a steady-state of SOC in the different treatments was almost obtained, ensuring that the basic starting level of SOC is sufficiently known to allow future calculations of changes in SOC following changes in parts of the long-term experiment.

Despite the already mentioned difficulties in quantifying SOC changes, comparisons between treatments might be possible because time could be excluded

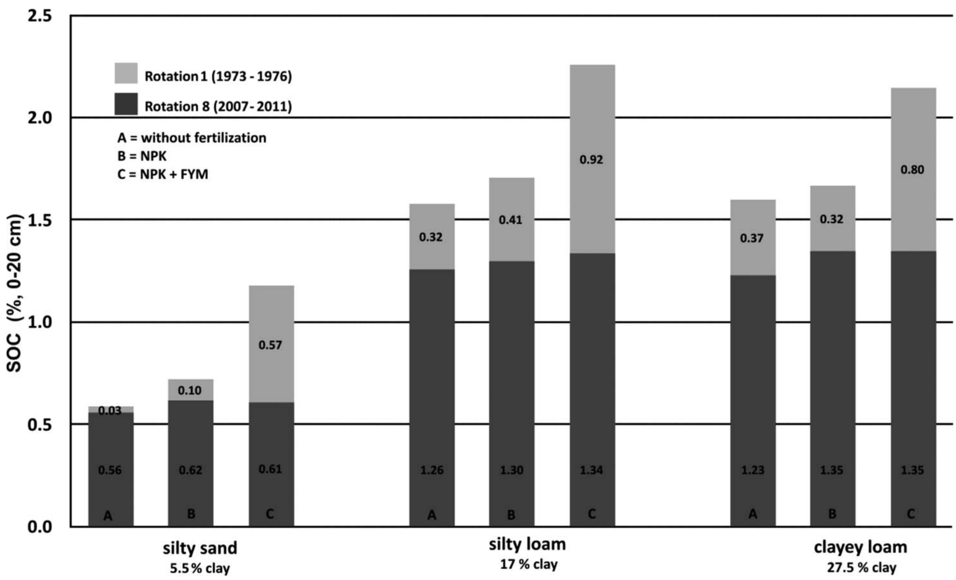

Figure 1. Effect of fertilization on soil organic carbon (SOC) content in the Box Plot Experiment Großbeeren (Rühlmann 2003) after 39 years (after fifth rotation 24 t ha^{-1} a^{-1} FYM). Crop rotation: *Brassica oleracea, Daucus carota, Cucumis sativus, Allium porrum, Apium graveolens* (since 1977).

as a variable. Unfortunately, most long-term experiments are not designed with real field replications and statistical significance cannot be obtained. However, it can be assumed that differences in SOC between treatments with and without FYM represent the amount of SOC accumulated or maintained. Indeed, increased yields and harvesting and root residues contribute to the accumulation of SOC and it is not possible to establish whether there has been an accumulation, in the case of a low initial content, or whether annually mineralized SOC has been compensated for, in case of a sufficient initial content.

Table 3 and Figure 2 demonstrate the effect of fertilization on SOC for 18 experiments. The results show large differences in SOC between the sites, but also fertilization-induced SOC differentiation. Compared with a SOC content of between 0.32 and 2.06% for unfertilized depleted treatments, the SOC content for the treatment 10 t ha^{-1} a^{-1} FYM + NPK ranges between 0.14 and 0.72% (0.11% in case of only 6 t ha^{-1} a^{-1} FYM). In 7 of these 18 experiments, the difference in SOC content without and with optimal fertilization was 0.2%, in four experiments, the difference was 0.2–0.3% and in only seven experiments was the difference $>0.3\%$; the average for all 18 experiments was 0.3%. Consequently, in the majority of the experiments, the effect of fertilization on amount of SOC was obtained with a FYM application of <15 t ha^{-1}a^{-1}, and in the LTE at Müncheberg, with application of 5 t ha^{-1} a^{-1} FYM; the reasons for the large differences between sites are hard to prove. On the one hand, the relationship between soil clay content and SOC was proved. On the other hand, extreme differences were recorded for the two sites at Vienna and Madrid, which had similar clay contents and annual precipitation, but differences of 6°C in annual average temperatures. Extensive studies using many LTEs under extreme site conditions are needed to unravel the cause–effect relations.

Using a simplified linear regression to trend out annual SOC changes, values between 100 and 500 kg ha^{-1} were calculated (calculation basis: 4500 t soil per ha for 0–30cm depth). As an exceptional site, the annual increase in SOC at the Madrid (La Higueruela) experiment, characterized by a clay-rich soil type, is >700 kg ha^{-1}. Annual SOC accumulation in top soil tends to increase with increasing clay content of the soils. Less pronounced fertilization-induced SOC accumulation was found in experiments at the Prague site, which had similar clay-rich soils and, like the Madrid site, only low average annual precipitation of $\sim$450 mm.

Soil tillage, which differs in the type of incorporation of organic fertilizers and harvesting and root residues, also affects distribution of POM in the top soil and therefore the amount of SOC. Whereas soil tillage using a conventional mouldboard plough homogenizes SOM within the ploughing layer, conservation soil tillage, and more particularly the zero tillage sowing technique, is accompanied by SOC accumulation in the upper layer of the top soil. In the long-term, the SOC contents of the lower part of the top soil will decrease due to the reduced input of organic matter (Pekrun and Claupein 1998). Compared with a medium ploughing depth (25 cm), chisel ploughing and flat ploughing (15 cm) caused an average SOC accumulation of 114 and 96 kg ha^{-1}, respectively, after 36 years of a soil tilling LTE near Leipzig (Hofmann et al. 2009); in the case of long-term no-ploughing management with zero till, 238 kg ha^{-1} SOC (Heyn and Zerr 2008) and 313 kg ha^{-1} SOC (Ehlers and Claupein 1994) were accumulated. Obviously, appropriate site-adapted soil tillage can contribute to SOC preservation in a similar way to fertilization. However, the original lower SOC contents will be reached after a short

Table 3. Effect of fertilization on SOC content (%) in the top soil of 18 selected European long-term experiments.

Country	Initial year	Sampling	Exp. years	SOC (% dry soil)				SOC range Min – Max	Mean annual SOC change
				without fertilization	NPK	10 t ha^{-1} a^{-1} FYM	FYM + NPK		
Austria									
Wien	1986	2007	21	2.06	2.2	2.1	2.24	0.18	0.0086
Czech Republic									
Prague	1955	2007–2010	53	1.34	1.44	1.75	1.62	0.28	0.0050
Germany									
Bad Lauchstädt	1902	2010	108	1.57	1.83	2.06	2.29	0.72	0.0067
Bad Salzungen	1966	2004–2008	41	0.49	0.76	0.67	1.01	0.52	0.0130
Berlin-Dahlem	1984	2006	24	0.55	0.62	0.67	0.69	0.14	0.0060
Groß Kreutz[a]	1967	2002–2004	37	0.42	0.58	0.68	0.88	0.46	0.0120
Halle/Saale	1949	2001+2003	53	0.97	1.08	1.14	1.14	0.17	0.0032
Methau	1966	2008–2010	43	1.10	0.99	1.35	1.47	0.37	0.0090
Müncheberg	1963	2003	40	0.45	0.46	0.50 (6 t ha^{-1})	0.56 (6 t ha^{-1})	0.11	0.0028
Rauischholzh.	1984	2001	17	0.85	0.89	0.86	1.12	0.27	0.0160
Speyer	1983	2011	28	0.58	0.40	0.8	0.81	0.23	0.0082
Spröda	1966	2008–2010	43	0.71	0.76	0.83	0.86	0.15	0.0035
Thyrow[b]	1937	2007–2010	71	0.34	0.42	0.60 (15 t ha^{-1})	0.70 (15 t ha^{-1})	0.36	0.0051
Thyrow[c]	1938	2007–2010	70	0.32	0.41	0.55	0.68	0.36	0.0051
Hungary									
Keszthely	1984	2005–2007	22	1.10	1.08	1.30	1.30	0.20	0.0090
Slovenia									
Rakican	1992	2008	16	1.04	1.01	1.17	1.21	0.17	0.0110
Jable	1992	2008	16	1.25	1.33	1.32	1.39	0.14	0.0090
Spain									
Madrid	1984	2010	26	0.55	0.61	0.95	1	0.45	0.0170

Notes: [a]Zimmer (2008a), [b]nutrient depletion experiment, [c]soil fertility experiment.

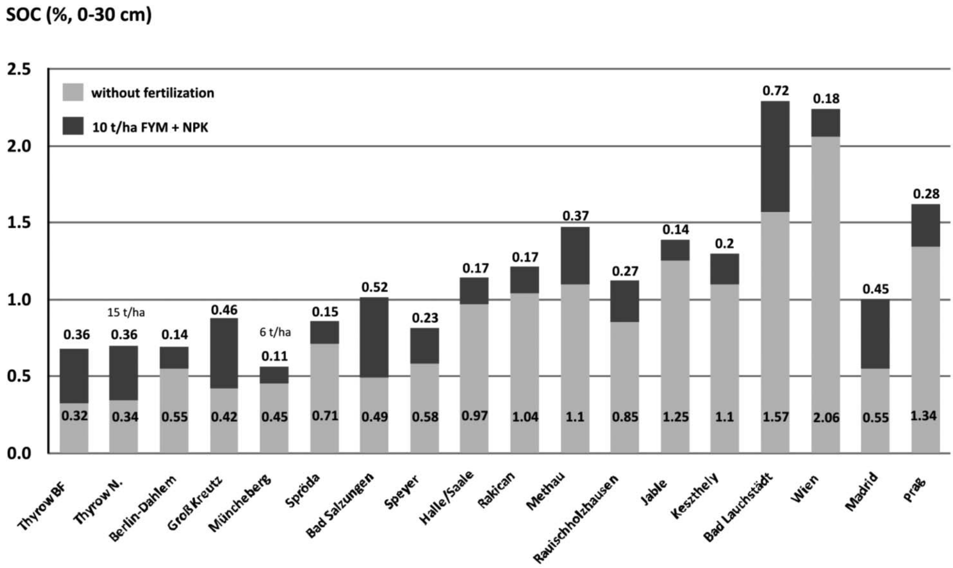

Figure 2. Effect of fertilization on soil organic carbon (SOC) contents in the top soil (0–30 cm) of 18 European long-term experiments – results from the first decade of the twenty-first century. Order of sites corresponding to increasing soil clay content, compare with Table 1.

period when returning to ploughing due to enhanced mineralization and CO_2 release (Koch and Stockfisch 2006).

Carbon sequestration

To evaluate the environmental relevance of organic fertilization, it is essential to know the amount of carbon accumulated in the soil and the efficiency of the accumulation. After a steady-state equilibrium is reached in the soil, the amount of C applied annually with organic fertilizers maintains the target SOC level and corresponds to the amount of SOC mineralized annually. The difference in the amount of SOC between unfertilized and FYM-fertilized treatments in LTEs can be used to estimate the C input (Table 4, derived from Table 3); showing the amount of C from organic fertilization, which enriched or maintained SOC compared with unfertilized treatments. The differences are very large and range between 3 and 41% due to factors like soil type, the duration of the experiment, differences in yields, starting situation and subsoil conditions. The calculated average of 20% represents a reference and is only applicable for FYM as organic fertilizer, but values correspond quite well to analyses for other LTEs (Körschens 2010); compared with the high reproductive capacity of carbon from FYM (Author Team 2004), the value for straw is only 60%; accordingly, only a small part of the carbon from straw will accumulate in the soil. Considering the low utilization of carbon from POM in humus formation, especially for straw, and its potential use as a renewable raw material as well as for energy production, its utilization should be balanced in light of climate protection.

Table 4. Effect of fertilization on SOC differences in the top soil of extreme treatments of 18 selected European long-term field experiments as well as the utilization of C applied with organic fertilizers.

Country	Initial (year)	Duration (years)	SOC difference between treatments '10 t ha^{-1} a^{-1} FYM' and 'without' (%)	SOC difference between treatments '10 t ha^{-1} a^{-1} FYM' and 'without' (t ha^{-1})	Utilization (%)
Austria					
Wien	1986	21	0.04	1.8	9
Czech Republic					
Prague	1955	62	0.41	18.5	30
Germany					
Bad Lauchstädt	1902	108	0.49	22.1	20
Bad Salzungen	1966	41	0.18	8.1	20
Berlin-Dahlem	1984	24	0.12	5.4	23
Groß Kreutz[a]	1967	37	0.26	11.7	32
Halle/Saale	1949	53	0.17	7.7	15
Methau	1966	43	0.25	11.3	26
Müncheberg	1963	40	0.05 (6 t ha^{-1})	2.3	10
Rauischholzhausen	1984	17	0.01	0.5	3
Speyer	1983	28	0.22	9.9	35
Spröda	1966	43	0.12	5.4	13
Thyrow NM[b]	1937	71	0.26 (15 t ha^{-1})	11.7	11
Thyrow BF[c]	1938	70	0.23	10.4	15
Hungary					
Keszthely	1984	22	0.2	9	41
Slovenia					
Jable	1992	16	0.07	3.2	20
Rakican	1992	16	0.13	5.9	37
Spain					
Madrid	1984	26	0.4	18	7
Average			0.2		20

Notes: [a]Zimmer (2008a), [b]nutrient depletion experiment, [c]soil fertility experiment.

Nitrogen uptake and balances

To quantify N dynamics and N balance, the same uncertainties as for SOC have to be considered, concerning a sufficient record of the changes in N stocks in the soil and also atmospheric N input. In many cases, only bulk deposition with precipitation is considered; these values decreased over time although total deposition (bulk deposition + gaseous deposition) is essential. In the past, total deposition was measured by the integrated total nitrogen immission (ITNI) method (Böhme et al. 2002) and this revealed an atmospheric N input of between 45 and 75 kg ha^{-1} a^{-1}. By considering the atmospheric N input, the frequently negative N balances at several sites can be explained where no decrease of nitrogen in soil is expected or measured. Nitrogen uptake by crops in unfertilized treatments ranged between 33 and 107 kg ha^{-1} (Table 5). The N uptake of 129 kg ha^{-1} a^{-1} in Prague confirmed known symbiotic N_2 fixation by lucerne (Table 5). In the extended Static Fertilization Experiment Bad Lauchstädt, 49 kg ha^{-1} a^{-1} N was taken up in the previously unfertilized treatment (previously 1.6% SOC), but in the previously

Table 5. Nitrogen uptake by crops in treatments without fertilization of selected European long-term experiments within selected periods.

Country	Initial year	Evaluation period	N uptake (kg N $ha^{-1}a^{-1}$)
Austria			
Wien	1986	1986–2006	107
Czech Republic			
Prague	1955	2001–2010	43
Prague 20% Luzerne	1955	2001–2010	129
Germany			
Bad Lauchstädt	1902	2001–2010	51
Bad Salzungen	1966	1993–2010	45
Halle/Saale	1948	1997–2006	70
Methau	1966	1999–2010	78
Müncheberg	1963	1982–2004	33
Rauischholzhausen	1984	1999–2008	80
Speyer	1984	2001–2010	36
Spröda	1966	1999–2010	55
Hungary			
Keszthely	1984	2005–2007	42
Slovenia			
Jable	1992	2001–2010	46
Rakican	1992	2001–2010	64
Spain			
Madrid	1984	2000–2011	47

organic and mineral fertilized treatment (15 t ha^{-1} a^{-1} FYM + NPK; previously 2.3% SOC) the value was 87 kg ha^{-1} a^{-1} (Körschens and Pfefferkorn 1998).

At Bad Lauchstädt, N balances correspond to the values given by Rathke et al. (2002) for the period 1991–2000. For N application doses up to 200 kg ha^{-1} a^{-1}, more N was taken up than was applied, indicating that crops partly use nitrogen from the atmospheric input. However, this is due mainly to favourable nature of the site, with a potential rooting depth of 2 m and a water-holding capacity of 500 L m^{-2} (Altermann et al. 2005), which is equal to the average annual precipitation at the site, ensuring that only in extremely wet years is nitrogen at risk of being washed out of the rooting zone. At other sites also, an apparent N utilization of 100% can be accounted for by N application doses up to 100 kg ha^{-1} a^{-1} for the Spröda site (sandy soil) and 150 kg ha^{-1} a^{-1} for the Methau site (loamy soil). The utilization of nitrogen from FYM is much lower, even if partial accumulation in the soil is assumed. In general, higher utilization of mineral nitrogen is recorded compared with nitrogen from FYM, with one exception, the Prague site (Kubát et al. 2003).

Rühlmann and von Gagern (2008) performed a cross-site analysis of N balances for LTEs in Brandenburg, including experiments M4 and P60 at Groß Kreutz (Zimmer 2008a, 2008b), the Müncheberg experiment V140 (Barkusky 2009) and the Box Plot Experiment at Großbeeren (Rühlmann 2003, 2008). With respect to the comparability of yields for different crops or crop rotations, normalization within each experiment was performed on a 100% basis for the highest average dry matter yield as the sum of the main crop and by-product. Comparing these experiments, it could be shown that the highest yield class (95–100%), which was connected with the lowest N loss (<50 kg ha^{-1} a^{-1}), could be achieved in the majority of experiments with mineral N fertilization only (partly in combination with a low N input from organic fertilizers of a broad C to N ratio; 18 kg ha^{-1} via pine bark in Großbeeren or 8 kg N ha^{-1} nitrogen from straw in Müncheberg). However, at the site at Groß Kreutz, high yield classes could only be achieved with a combination of organic and mineral fertilization. In most cases, these high yields were connected with N losses of >50 kg ha^{-1}.

Summary and conclusions

- The soil improving effect of SOM on yields, i.e. the effect which cannot be reached by a sufficient and equivalent nutrient supply, was 6% (average of 350 yield comparisons form 16 LTEs at 12 different sites, the majority for the period 2001–2010), being lowest for winter wheat (3%) and highest for potatoes (9%).
- SOC contents in the topsoil of long-term (decades) unfertilized treatments range between 0.36 and 1.57% for 18 analysed sites; SOC differences between unfertilized and optimally fertilized treatments are on average 0.3%. Considering that under farm conditions, the 'unfertilized' treatment (i.e. no mineral or organic fertilization over a period of decades) does not exist, relevant SOC differences for farms are often $<0.2\%$ (or <9 t ha^{-1} SOC).
- The course of management-induced (e.g. crop rotation, fertilization, soil tillage) changes in SOC depends on the starting level of SOC; equivalent treatments may lead to an increase in SOC from a low starting level, but a decrease from a high starting level.
- Bare fallow affects the soil carbon budget most strongly; without organic matter input from harvesting and root residues, the SOC content decreases considerably after a short period of 10 years.
- In light of yield realization, together with environmentally acceptable N and C balances, FYM application doses of 10 t ha^{-1} a^{-1} are shown to be optimal, levels on average below the amount calculated from the German VDLUFA Position Paper 'Humus Balance Method' (Author Team 2004).
- Increasing the percentage of organic fertilizers for the total C and N input will have adverse effects on C and N balances.
- To evaluate nitrogen utilization by crops, an atmospheric N input (bulk deposition, gaseous immission, a symbiotic N_2 fixation) of up to 50 kg ha^{-1} a^{-1} has to be considered.
- In Germany, potential use of crop land as a carbon sink is of low relevance. Under steady-state conditions, only that SOC will be replaced (by organic input) that was released into atmosphere by SOM mineralization. Only at SOM-depleted sites, can SOC accumulate until an optimum is reached. However, the utilization of organic materials at only 10–20% over two decades is low.

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Appendix 1. International long-term experiments (ILTE) contributing to the International Working Group ILTE/IOSDV.

Location/Experiment/*Institution*	Objectives	Started	Soil	Avererage temperature (°C)	Precipitation (mm)
Austria: Austrian Agency for Health and Food Safety (AGES)					
Fuchsenbigl (Marchfeld)/Soil tillage experiment	Effects of different tillage treatments on crop and soil parameters.	1988	sandy loam	9.4	529
Fuchsenbigl (Marchfeld)/ Potassium fertilizer experiment	Effects of different amounts and forms of potassium fertilization on crop and soil parameters.	1956	sandy loam	9.4	529
Grabenegg (Wieselburg, Alpine foothills)/Potassium fertilizer experiment	Effects of different amounts and forms of potassium fertilization on crop and soil parameters.	1954	silty loam	8.4	778
Rutzendorf (Marchfeld)/Soil fertility effect of P fertilization and of the management of crop residues	Effects of different P fertilizer doses and of incorporation/removal of crop residues on crop and soil parameters.	1982	sandy loam	9.4	529
Grabenegg (Wieselburg, Alpine foothills)/Soil fertility effect of P fertilization and of the management of crop residues	Effects of different P fertilizer doses and of incorporation/removal of crop residues on crop and soil parameters.	1986	silt	8.4	778
Ritzlhof (Upper Austria near Linz)Compost fertilization/ experiment	Effects of long term compost application compared to different N fertilization on yield and soil	1991	loamy silt	8.5	753
Czech Republic: Crop Research Institut Prag-Ruzyne, Drnovska 5					
Prag-Ruzyně/DP 01	Effect of different fertilization systems on nutrient uptake, yields and soil properties.	1955	clay–loam	7.9	472
Ivanovice/DP 02,VOP	Effect of organic and mineral N fertilization on nutrient uptake, yields, quality of crops and soil fertility.	1955	loam	8.9	542

(*continued*)

Appendix 1. (*Continued*).

Location/Experiment/*Institution*	Objectives	Started	Soil	Avererage temperature (°C)	Precipitation (mm)
Čáslav/DP 02, VOP	Effect of organic and mineral N fertilization on nutrient uptake, yields, quality of crops and soil fertility.	1955	loam	8.9	555
Lukavec/DP 02, VOP	Effect of organic and mineral N fertilization on nutrient uptake, yields, quality of crops and soil fertility.	1955	sandy loam	7.26	674
Ivanovice/DP 04	Effect of soil improving factors in mono-culture systems.	1965	loam	8.90	542
Trutnov/DP 05	Effect of organic fertilization and straw incorporation on yields and soil fertility.	1966	sandy loam	7.5	750
Hněvčeves/DP 09	Effect of a cereal dominated crop rotation and of organic and mineral fertilization on yields.	1971	clay–loam	8.2	573
Hněvčeves/DP 10	Effect of crop rotation and herbicide application on weed growth.	1971	clay–loam	8.2	573
Pernolec/DP 10	Effect of crop rotation and herbicide application on weed growth.	1971	sand–loam	7.1	559
Pernolec/DP 11	Effect of pig slurry application on soil fertility, nutrient cycling and soil organic matter.	1972	sand–loam	7.1	559
Kostelec/DP 11	Effect of pig slurry application on soil fertility, nutrient cycling and soil organic matter.	1972	sand–loam	7.6	681
Hněvčeves/DP 13, GS140	Effect of organic and mineral fertilization on yields and soil fertility.	1979	clay–loam	8.2	573

(*continued*)

Appendix 1. (*Continued*).

Location/Experiment/*Institution*	Objectives	Started	Soil	Avererage temperature (°C)	Precipitation (mm)
Kostelec/DP 13, GS140	Effect of organic and mineral fertilization on yields and soil fertility.	1979	sand–loam	7.6	681
Pernolec/DP 13, GS140	Effect of organic and mineral fertilization on yields and soil fertility.	1979	sand–loam	7.1	559
Humpolec/DP 13, GS140	Effect of organic and mineral fertilization on yields and soil fertility.	1979	sand–loam	6.5	667
Vysoké/DP 13, GS140	Effect of organic and mineral fertilization on yields and soil fertility.	1979	loamy sand	6.5	995
Ivanovice/DP 15	Effect of soil tillage and crop rotation on yields and soil fertility.	1988	loam	8.9	542
Germany					
Bad Lauchstädt/Static Fertilization Experiment (SFE) and Extended SFE/*Helmholtz Centre Environmental Research - UFZ*	Long-term fertilization impact on soil ecological functions and processes in agro-ecosystems	1902		8.8	486
		1978	loam		

(*continued*)

Appendix 1. (*Continued*).

Location/Experiment/*Institution*	Objectives	Started	Soil	Avererage temperature (°C)	Precipitation (mm)
Bad Salzungen/*Thuringian Country Institution for Agriculture (TLL)*	Different org + min. fert. (L 28)	1966	loamy sand	8.1	568
Berlin–Dahlem/Static soil management experiment/*Humboldt-University Berlin*	Long-term management impact (ploughing depth, liming, P and FYM application) on yield potential of a sandy soil	1923	sand	9.9[a]	562[a]
Etzdorf /*Sugar beet crop rotation experiment*/*Martin Luther University Halle-Wittenberg*	Long-term impact of sugar beet rate in crop rotation on yield and soil properties	1970	loam	9.0	453
Gießen/Depletion experiment/*Justus Liebig University Gießen*	Long-term impact of nutrient depletion on soil properties and yield potential as compared to sub-optimal and optimal nutrient supply	1954	silty clay	9.0	650
Gießen/BSG (Biological nitrogen fixation)[b]/*Justus Liebig University Gießen*	Comparative effect of nitrogen fixing plants versus cereals on yield and quality of the following crops	1982	silty clay	9.0	650

Appendix 1. (*Continued*).

Großbeeren/Box plot experiment/*Leibniz Institute of Vegetable and Ornamental Crops*	Effect of mineral and organic nitrogen fertilization on soil properties, vegetable yield and quality.	1973	silty sand	8.4	527
Großbeeren/Box plot experiment/*Leibniz Institute of Vegetable and Ornamental Crops*	Effect of mineral and organic nitrogen fertilization on soil properties, vegetable yield and quality.	1973	sandy loam	8.4	527
Großbeeren/Box plot experiment/*Leibniz Institute of Vegetable and Ornamental Crops*	Effect of mineral and organic nitrogen fertilization on soil properties, vegetable yield and quality.	1973	clayed silt	8.4	527
Großbeeren/Mineral and organic nitrogen fertilization experiment/ *Leibniz Institute of Vegetable and Ornamental Crops*	Diff. FYM + min-N vegetable	1989	silty sand	8.4	527
Halle/Eternal Rye Experiment/ *Martin Luther University Halle-Wittenberg*	Mineral + organic fertilization	1878	loamy sand	9.2	494
Halle Feld F	Mineral + organic fertilization	1949	sandy loam	9.2	494
Halle Feld A	Ca fertilization	1949	sandy loam	9.2	494
Halle, Feld C	K fertilization	1949	sandy loam	9.2	494
Halle, Feld D	P fertilization	1949	sandy loam	9.2	494

Appendix 1. (*Continued*).

Methau/*Saxon Country Institution for Environment, Agriculture and Geology*	Combined org. + min. fert. (L 28)	1966	loam	8.2	680
Müncheberg/Incremental nutrient experiment/ *Leibniz Centre for Agricultural Landscape Research (ZALF)*	Nutritional effect of mineral nitrogen fertilization, farmyard manure and straw on yield and selected soil parameters.	1963	sandy loam	8.2 (1951–1980) 8.4 (1980–2000)	527 (1951–1980) 528 (1951–2000)
Rauischholzhausen/Crop rotation experiment 'Hinter den Gärten'/*Justus Liebig University Gießen*	Evaluation of different crop-rotation.	1983	silty loam	8.1	595
Speyer/Organic matter experiment/*Institute for Agricultural Investigation and Research Speyer*	Effect of different organic fertilizers and irrigation on plant growth and quality of crops in different crop rotations.	1958	sand	10.0	593
Speyer/Sewage sludge experiment/*Institute for Agricultural Investigation and Research Speyer*	Accumulation of heavy metals in soil and plants depending on frequency and amount of sewage sludge application.	1981	sand	10.0	593
Spröda/*Saxon Country Institution for Environment, Agriculture and Geology*	Combined organic + mineral fertilization (L 28)	1966	loamy sand	8.9	465
Thyrow/Static fertilization and irrigation experiment/ *Humboldt University Berlin*	Effect of nitrogen fertilization, straw incorporation and irrigation on yield, organic matter and nutrient balance of the soil. (From 1969 irrigation)	1937	sand	9.2[c]	510[3]

(*continued*)

Appendix 1. (*Continued*).

Thyrow/Static nutrient depletion experiment/ *Humboldt Univiversity Berlin*	Effect of nutrient depletion (N,P,K), liming and organic fertilization (farmyard manure) on yield, soil pH, and soil nutrient and organic matter balance.	1937	sand	9.2[c]	510^3
Thyrow/Static soil fertility experiment/*Humboldt Univiversity Berlin*	Effect of the type and amount of organic fertilization, soil amelioration with clayey soil, and nitrogen fertilization on yield and soil nutrient and organic matter balance. (from 1977 N fertilization)	1938	sand	9.2[c]	510^3
Thyrow/Straw and crop rotation experiment/ *Humboldt Univiversity Berlin*	Effect of nitrogen fertilization, straw incorporation and crop rotation on yield and soil nutrient and organic matter balance.	1976	sand	9.2[c]	510^3
Thyrow/Land use experiment/ *Humboldt Univiversity Berlin*	Effect of conventional and conserving soil tillage on yield potential, soil organic matter content and carbon sequestration in sandy soils considering biomass production as alternative source of energy.	2005	sand	9.2[c]	
Hungary: University of Pannonia Georgikon Faculty, Department of Crop, Production and Soil Science					
Keszthely	Effect of organic and mineral fertilization on yields and soil fertility.	1963	loam	10.5	683
Keszthely	P and K fertilization.	1963	loam	10.5	683
Keszthely	Different N-levels in maize monoculture.	1969	loam	10.5	683

(*continued*)

Appendix 1. (*Continued*).

Keszthely	Effect of conventional and conserving soil tillage on yields, SOM and soil physical properties in winter wheat and maize.	1974	loam	10.5	683
Keszthely	Effect of crop rotation on yields and soil fertility.	1963	loam	10.5	683
OMTK/UMD: Hungarian mineral fertilization long-term experiments (OMTK/UMD)					
Keszthely	This experimental series belongs to the only few long-term fertilization experiments of the world which are laid out in an uniform scheme at 9 sites under different agro-ecological management conditions in Hungary with a duration of more than 30 years.	1967	loam	10.3	683
Mosonmagyaróvár		1967	loam	9.8	594
Bicsérd		1967	loam	10.4	661
Iregszemcse		1967	loam	10.3	619
Nagyhörcsök		1967	loam	10.3	559
Karcag		1967	loam	10.2	527
Kompolt		1967	loam	10.1	542
Putnok		1967	loam	8.8	581
Hajdúböszörmény		1967	loam	10.3	585

Notes: [a]Period 1981–2010. [b]It is intended to replace the fallow by energy crops. [c]Period 1981–2010.

Appendix 2. International organic nitrogen fertilization long-term experiments (IOSDV).

Country	Location	Initial year	Clay content (%)	Average annual temperature (°C)	Annual precipitation (mm)
Austria	Wien	1986	25.0	9.5	489
Czech Republic	Lucavec	1983	13.0	7.3	674
	Ivanovice	1983	28.0	8.9	542
Estonia	Tartu	1989	7.7	4.8	582
Germany					
	Berlin-Dahlem	1984	4.3	9.3	550
	Puch	1984	15.0	8.0	920
	Rauischholzhausen	1984	17.0	8.0	583
	Speyer	1983	8.9	10.0	593
Hungary	Keszthely	1984	21.3	10.2	635
Poland	Wroclaw-Swojec	1996	16.0	8.6	545
Romania	Iasi	1985		9.5	500
Slovenia	Jable, bei Ljubljana	1992	16.8	9.5	1345
	Rakican	1992	14.7	10.5	796
Spain	La Higueruela near Madrid	1984	26.8	12.0	430
	La Higueruela (ISDV)	1973	26.8	12.0	430