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Effect of crop residue incorporation on soil organic carbon and greenhouse gas emissions in European agricultural soils

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Abstract

Soil organic matter (SOM) improves soil physicochemical and biological properties, and the sequestration of carbon in SOM may mitigate climate change. Soil organic carbon (SOC) often decreases in intensive cropping systems. Incorporation of crop residues (CR) may be a sustainable management practice to maintain the SOC levels and to increase soil fertility. This study quantifies the effects of CR incorporation on SOC and greenhouse gas (GHG) emissions (CO_2 and N_2O) in Europe using data from long-term experiments. Response ratios (RRs) for SOC and GHG emissions were calculated between CR incorporation and removal. The influence of environmental zones (ENZs), clay content and experiment duration on the RRs was investigated. We also studied how RRs of SOC and crop yields were correlated. A total of 475 RRs were derived from 39 publications. The SOC increased by 7% following CR incorporation. In contrast, in a subsample of cases, CO_2 emissions were six times and N_2O emissions 12 times higher following CR incorporation. The ENZ had no significant influence on RRs. For SOC concentration, soils with a clay content >35% showed 8% higher RRs compared with soils with clay contents between 18 and 35%. As the experiment progressed, RR for SOC concentration increased. For N_2O emissions, RR was significantly greater in experiments with a duration <5 yr compared with 11–20 yr. No significant correlations were found between RR for SOC concentration and yields, but differences between sites and study durations were detected. We suggest that a long duration of crop residue incorporation is a win-win scenario under a continental climate. We conclude that CR incorporation is important for maintaining SOC, but its influence on GHG emissions should be taken into account as well.

Keywords: Carbon dioxide, nitrous oxide, soil organic carbon, response ratio, crop residue management, climate change

Introduction

Soil organic matter (SOM) improves soil physical (e.g. increased aggregate stability), chemical (e.g. cation exchange capacity) and biological (e.g. biodiversity, earthworms) properties, and it mitigates climate change by sequestering carbon in soils (Lal, 2013). Currently, as much as 25–75% of the soil organic carbon (SOC) in the world's agricultural soils may have been lost due to intensive agricultural practices (Lal, 2013), and about 45% of European soils exhibit low organic matter contents (European Commission, 2006). The decline of OM is one of the major threats to soils described by the European Commission (European Commission, 2006).

Globally, approximately four billion tons of crop residues are produced (Chen *et al.*, 2013). Removal of crop residues has a negative effect on SOC, but an estimated 25–50% of

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crop residues could be harvested without threatening soil functions (Blanco-Canqui, 2013). Harvesting crop residues may be beneficial for farmers because residues can be used as livestock bedding, sold or thermally utilized. Harvesting residues also fits reduced or no-tillage farming operations because the soil will be less disturbed due to no ploughing of crop residues into the soil. Incorporation of crop residues may be a sustainable and cost-effective management practice to maintain the ecosystem services provided by soils, the SOC levels and to increase soil fertility in European agricultural soils (Perucci *et al*., 1997; Powlson *et al*., 2008). In particular, Mediterranean soils with small SOC concentrations (Aguilera *et al*., 2013), and areas where stockless croplands predominate (Kismányoky & Toth, 2010; Spiegel *et al*., 2010b), could benefit from this management practice. Nonetheless, crop residue incorporation increases the SOC concentrations less than does farmyard manure (Cvetkov *et al*., 2010) or slurry (Triberti *et al*., 2008). For greenhouse gas (GHG) emissions, both positive and negative effects have been observed following crop residue incorporation (e.g. Abalos *et al*., 2013). Emissions of CO_2 indicate heterotrophic microbial activity and particularly mineralization (Baggs *et al*., 2003), whereas N_2O emissions indicate both nitrification and denitrification processes (Chen *et al*., 2013).

The response of soil properties to management practices may depend on various factors such as soil temperature and soil moisture content, soil clay content (Körschens, 2006; Chen *et al*., 2013) or duration of the experiment (Smith *et al*., 2012; Chen *et al*., 2013). Metzger *et al*. (2005) presented a stratification of environmental zones (ENZs) in Europe, which is based on climate, geology and soils, geomorphology, vegetation and fauna. It can be used to compare the response of soil to management practices across Europe (Jongman *et al*., 2006). In their meta-analysis, Chen *et al*. (2013) showed that the clay content was a good predictor for N_2O emissions following crop residue incorporation. Especially in the case of soil processes, the experiment duration improves the accuracy of data. Accordingly, long-term experiments are very important when assessing the impact of a management practice on soil (Körschens, 2006). Effects of crop residue incorporation on SOC and GHG emissions have been studied across the world (Chen *et al*., 2013; Liu *et al*., 2014), but the results differ due to the wide range of systems inherent in a global coverage. The lack of studies focusing on both SOC and GHG emissions (Ingram & Fernandes, 2001), calls for an analysis of European results. An analysis of long-term experiments (LTEs) helps integrate current knowledge in Europe and provides guidance for policy development.

This study was designed to quantify the effects of crop residue incorporation on SOC and GHG emissions in varying environmental zones in Europe, using the published results of LTEs. Specifically, we addressed the following questions:

(i) Are environmental zones important for analysing the effects of crop residue incorporation on SOC concentration, as well as on GHG emissions (CO_2, N_2O)?
(ii) Does the effect of crop residue incorporation on SOC and GHG emissions vary with differences in clay content?
(iii) Does the duration of the experiment influence the response ratios of SOC and GHG emissions following crop residue incorporation?
(iv) Does the RR of GHG emissions, following residue incorporation, vary with experimental setup and crop residue type?
(v)Are RRs for SOC concentrations and yields correlated?

We hypothesized that the response ratios of SOC increase the most in the Nemoral ENZ due to cool temperatures, particularly in soils with a large clay content due to interactions between SOC and clay minerals, and furthermore they increase with time. The response ratios of GHG emissions were expected to be least in the Nemoral ENZ, and to decrease with time. We expected the response ratios of GHG emissions to be larger in laboratory than field experiments due to more favourable conditions for the microorganisms, such as optimal soil water content. The RR of GHG emissions was expected to be greater with incorporation of low-C/N-ratio crop residues (hereafter referred to as 'vegetative material' such as sugar beet, potato or leafy greens compared with high-C/N-ratio crop residues, hereafter referred to as 'cereal' such as barley, wheat or maize residue incorporation). Further, we expected to observe a positive correlation between yields and SOC concentrations, as higher yields would result in more residues and greater accumulation of SOC.

Materials and methods

Data sources

A detailed literature review was conducted concerning scientific publications that had reported on long-term agricultural experiments in Europe. This yielded a total of 475 response ratios from 39 publications (Table 1), 50 experiments in 15 countries. An online database was created, which included 46 field experiments and four laboratory experiments that covered 10 European Environmental Zones (ENZs), as defined by Metzger *et al*. (2005), and four aggregated ENZs (Figure 1, Table 2). Most of the data were published in peer-reviewed scientific journals, while a smaller fraction was published in national technical journals and conference proceedings. The publications report on measurements of SOC concentration and CO_2 and N_2O emissions from pairwise comparisons of crop residue incorporation and crop residue removal management practices. The minimum requirements for data being

Table 1 Summary description of sites included in the analysis

Experiment No.	Experiment	Country	Location	Environmental zone[a]	Start year	Soil texture	References
Field studies							
1	Ås	Norway	59°39′N 10°47′E	NEM	1953	Clay loam	Uhlen (1991)
2	Øsaker	Norway	59°23′N 11°02′E	NEM	1963	Silty clay loam	Uhlen (1991) and Børresen (1999)
3	Ultuna	Sweden	59°00′N 17°00′E	NEM	1956	Clay loam	Börjesson *et al.* (2012)
4	Foulum	Denmark	56°30′N 09°34′E	ATN	1997	Sandy loam	Mutegi *et al.* (2010) and Petersen *et al.* (2011)
5	Studsgaard	Denmark	56°05′N 08°54′E	ATN	1969	Loamy sand	Powlson *et al.* (2011)
6	Askov	Denmark	55°28′N 09°07′E	ATN	1894	Sandy loam	Powlson *et al.* (2011)
7	Rønhave	Denmark	54°54′N 09°47′E	ATN	1969	Sandy loam	Powlson *et al.* (2011)
8	Edinburgh	UK	55°57′N 03°11′W	ATN	1995	Clay loam	Ball *et al.* (1990)
9	Morley	UK	52°34′N 01°06′W	ATN	1984	Sandy loam	Nicholson *et al.* (1997) and Powlson *et al.* (2011)
10	Gleadthorpe	UK	53°13′N 01°05′W	ATC	1984	Loamy sand	Nicholson *et al.* (1997)
11	Woburn	UK	51°59′N 00°37′W	ATC	1938	Sandy loam	Murphy *et al.* (2007) and Powlson *et al.* (2011)
12	Rothamsted	UK	51°48′N 00°21′W	ATC	1852	Clay	Powlson *et al.* (2011)
13	Wye Estate	UK	51°10′N 00°56′E	ATC	1999	Silty loam	Baggs *et al.* (2003)
14	Cologne	Germany	50°56′N 06°57′E	ATC	1969	Silt	Marschner *et al.* (2003)
15	Gembloux	Belgium	50°33′N 04°41′E	ATC	1959	Silty loam	Powlson *et al.* (2011)
16	Wierzchucinek	Poland	53°15′N 17°47′E	CON	1979	Sandy loam	Janowiak (1995)
17	Rostock	Germany	54°05′N 12°08′E	CON	1954	Loam	Leinweber & Reuter (1992)
18	Müncheberg	Germany	52°30′N 14°08′E	CON	1962	Silty loam	Rogasik *et al.* (2001)
19	Grossbeeren 1	Germany	52°21′N 13°18′E	CON	1972	Loamy sand	Rühlmann & Ruppel (2005), Rühlmann (2006) and MLUV (2009)
20	Grossbeeren 2	Germany	52°21′N 13°18′E	CON	1972	Sandy loam	Rühlmann & Ruppel (2005), Rühlmann (2006) and MLUV (2009)
21	Grossbeeren 3	Germany	52°21′N 13°18′E	CON	1972	Silt	Rühlmann & Ruppel (2005), Rühlmann (2006) and MLUV (2009)
22	Braunschweig	Germany	52°18′N 10°27′E	CON	1952	Silty loam	Rogasik *et al.* (2001)
23	Spröda	Germany	51°32′N 12°25′E	CON	1966	Sandy loam	Albert & Grunert (2013)
24	Methau	Germany	51°04′N 12°51′E	CON	1966	Silty loam	Albert & Grunert (2013)
25	Puch	Germany	48°11′N 11°13′E	CON	1984	Silty loam	Hege & Offenberger (2006)
26	Suchdol	Czech Republic	49°57′N 15°09′E	CON	1997	Loam	Nedved *et al.* (2008)
27	Lukavec	Czech Republic	49°33′N 14°59′E	CON	1997	Sandy loam	Nedved *et al.* (2008)
28	Alpenvorland	Austria	48°07′N 15°08′E	CON	1986	Silty loam	Spiegel *et al.* (2010a)
29	Marchfeld	Austria	48°13′N 16°36′E	PAN	1982	Sandy loam	Spiegel *et al.* (2010a)
30	Vienna	Austria	48°11′N 16°44′E	PAN	1986	Loamy sand	Spiegel *et al.* (2010b)
31	Keszthely	Hungary	46°44′N 17°13′E	PAN	1960	Sandy loam	Kismanyoko & Toth (2013)
32	Trutnov	Czech Republic	50°33′N 15° 53′E	ALS	1966	Sandy loam	Simon *et al.* (2013)
33	Rakican	Slovenia	46°38′N 16°11′E	ALS	1993	Loamy sand	Cvetkov & Tajnsek, 2009, Cvetkov *et al.* (2010) and Tajnsek *et al.* (2013)
34	Jable	Slovenia	46°08′N 14°34′E	ALS	1993	Silty loam	Cvetkov & Tajnsek (2009)
35	Grignon	France	45°39′N 06°22′E	ALS	1963	Loam	Powlson *et al.* (2011)
36	Doazit	France	43°41′N 00°38′W	LUS	1967	Loamy sand	Plénet *et al.* (1993)
37	Serreslous	France	43°40′N 00°40′W	LUS	1967	Silty loam	Plénet *et al.* (1993) and Lubet *et al.* (1993)

Table 1 (continued)

Experiment No.	Experiment	Country	Location	Environmental zone[a]	Start year	Soil texture	References
38	Tetto Frati	Italy	44°53′N 07°41′E	MDM	1992	Loam	Grignani *et al*. (2007), Bertora *et al*. (2009) and Zavattaro *et al*. (2012)
39	Padova	Italy	45°21′N 11°58′E	MDN	1966	Clay loam	Lugato *et al*. (2006)
40	Papiano	Italy	42°57′N 12°20′E	MDN	1971	Loam	Bianchi *et al*. (1994) and Perucci *et al*. (1997)
41	Foggia 1	Italy	41°27′N 15°32′E	MDN	1977	Clay	Maiorana (1998) and Maiorana *et al*. (2004)
42	Foggia 2	Italy	41°27′N 15°32′E	MDN	1990	Clay	Maiorana (1998) and Maiorana *et al*. (2004)
43	Almacelles 1	Spain	41°43′N 00°26′E	MDS	2010	Clay loam	Biau *et al*. (2013)
44	Almacelles 2	Spain	41°43′N 00°26′E	MDS	2010	Loam	Biau *et al*. (2013)
45	El Encín	Spain	40°32′N 03°17′W	MDS	2010	Clay loam	Meijide *et al*. (2010) and Abalos *et al*. (2013)
46	La Chimenea	Spain	40°03′N 03°31′W	MDS	2009	Silty clay loam	Sanz-Cobena *et al*. (2014)
Laboratory studies							
47	Flevopolder	The Netherlands	52°30′N 05°28′E	ATC	1999	Clay	Velthof *et al*. (2002)
48	Wageningen	The Netherlands	51°58′N 05°39′E	ATC	1999	Sand	Velthof *et al*. (2002)
49	Wijnandsrade	The Netherlands	50°54′N 05°52′E	ATC	N/A	Silty loam	Cayuela *et al*. (2014)
50	Wye Estate	UK	51°10′N 00°56′E	ATC	1999	Silty loam	Garcia-Ruiz & Baggs (2007)

[a]Environmental zone assigned according to Metzger *et al*. (2005): NEM, Nemoral; ATN, Atlantic North; ATC, Atlantic Central; CON, Continental; PAN, Pannonian; ALS, Alpine South; LUS, Lusitanian; MDM, Mediterranean Mountains; MDN, Mediterranean North; MDS, Mediterranean South.

included were that the studies had i) replicates and ii) paired treatments that compared crop residue incorporation and removal. Further, we only included experiments in which crop residue incorporation and removal were investigated under the same climatic and soil conditions, as well as having similar fertilizer application levels. For CO_2 and N_2O emissions, data from long-term experiments were scarce. For these variables, shorter experiment durations and laboratory experiments were included in the database. For this analysis, mostly publications reporting data in tables, which could be directly transferred into the database, were used. Data given in figures were extracted using the program WebPlotDigitizer (Rohatgi, 2013).

Data preparation

For each pairwise comparison, a response ratio (RR) was calculated as:

$$RR = \text{property}_I/\text{property}_R$$

where property_I is the SOC concentration, CO_2 emission or N_2O emission in crop residue incorporation management practice, and property_R is the SOC concentration, CO_2 emission or N_2O emission in crop residue removal management practice. $RR > 1$ was assumed to be an improvement in SOC concentrations, whereas $RR > 1$ for CO_2 and N_2O emissions was assumed to be an undesirable increase in GHG emissions.

Data aggregation

In some cases, it was possible to derive more than one comparison from an experiment, for example when they report on multiple years or multiple contrasting managements. For stepwise linear multiple regressions and one-way analyses of variance (ANOVA), we used a single average of the response ratios for each experiment to aggregate multiple within-experiment response ratios prior to a between-study analysis (Lajeunesse, 2011). These averages were weighted based on the number of response ratios (sample size) from the experiments, because in many publications the standard deviation (SD) and number of samples (*n*) were missing.

Data analysis

The statistical analyses were performed using the IBM SPSS Statistics 20 software package for Mac. The normality of data was checked with Shapiro–Wilk's test. All data on SOC concentration and GHG emissions (CO_2 and N_2O) were not normally distributed, thus log-transformed before the statistical analyses to obtain homogeneity of variances. A stepwise linear multiple regression was used to identify the significant continuous variables (temperature, precipitation,

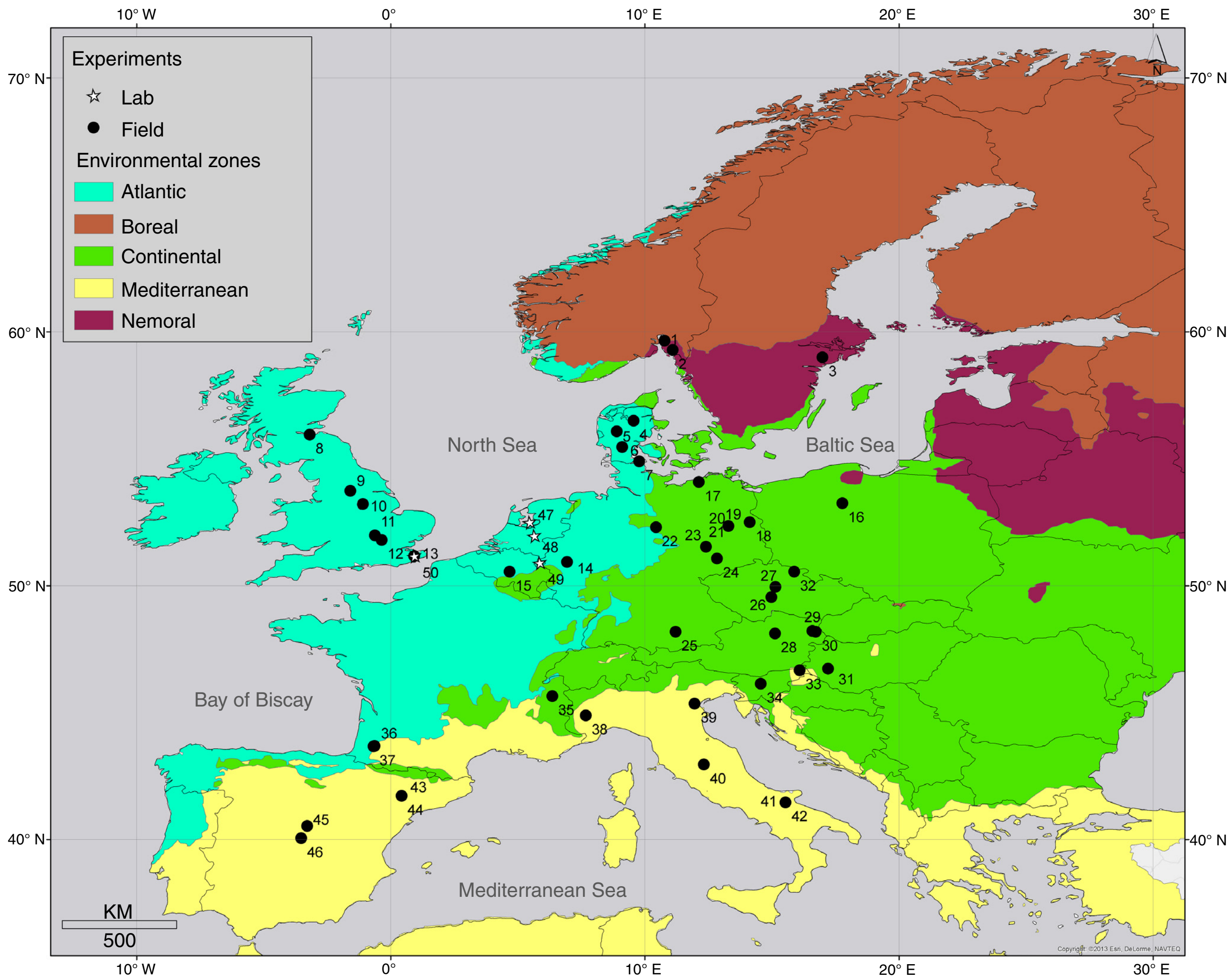

Figure 1 Map of the experiment locations and their distribution across the aggregated environmental zones (Nemoral, Atlantic, Continental, Mediterranean).

clay content, duration of the experiment were tested) on RR of SOC concentration and GHG emissions (Table 3). To strengthen our analyses, the effect of the variables ENZ, clay content and experiment duration (as aggregated into specific levels in Table 2) were investigated with ANOVA with Tukey's significance test ($P < 0.05$) as a *post hoc* test. Correlations between variables were presented in Pearson's correlation coefficients.

Table 2 Aggregated variables and specific levels of each variable

Variable	Specific levels			
ENZ[a]	Nemoral (NEM)	Atlantic (ATN, ATC, LUS)	Continental (CON, PAN, ALS)	Mediterranean (MDM, MDN, MDS)
Clay %	<18%	18–35%	>35%	
Experiment duration[b]	<5 yr	5–10 yr	11–20 yr	>20 yr

[a]Environmental zone assigned according to Metzger *et al.* (2005): NEM, Nemoral; ATN, Atlantic North; ATC, Atlantic Central; CON, Continental; PAN, Pannonian; ALS, Alpine South; LUS, Lusitanian; MDM, Mediterranean Mountains; MDN, Mediterranean North; MDS, Mediterranean South. [b]Experiment duration: years between the beginning of the experiment and the measurement.

Table 3 Significant results of multiple regressions

LOG RR of SOC concentration					
	R^2	F	P	n	
Model	0.140	34.385	<0.0001	213	
Variables	Coefficient	SE	95% CI	T	P
Intercept	0.008	0.004	0.001 to 0.016	2.125	0.035
Duration	0.001	0.0002	0.0006 to 0.0012	5.864	<0.0001

LOG RR of CO_2 emissions					
	R^2	F	P	n	
Model	0.983	1297.063	<0.0001	41	
Variables	Coefficient	SE	95% CI	T	P
Intercept	0.494	0.012	0.469 to 0.159	40.608	<0.0001
Clay content	−0.018	0.001	−0.019 to −0.017	−36.015	<0.0001

LOG RR of N_2O emissions					
	R^2	F	P	n	
Model	0.752	44.845	<0.0001	37	
Variables	Coefficient	SE	95% CI	T	P
Intercept	0.5587	0.265	0.048 to 1.126	2.212	0.034
Clay content	0.098	0.017	0.068 to 0.133	5.721	<0.0001
Temperature	−0.185	0.052	−0.289 to −0.080	−3.579	0.001

SE, standard error; CI, confidence interval.

Results

Crop residue incorporation increased the SOC concentration on average by 7% (Figure 2), whereas CO_2 emissions were increased almost sixfold and N_2O emissions more than 12-fold on average (n = 84 and 97, respectively). Multiple regressions revealed that experiment duration had highest effect on SOC concentration, explaining 14% of the variation (Table 3). Response ratio (RR) of SOC concentration was 12% greater in experiments with >20 yr duration, compared with experiments with duration <5 yr. Ninety-eight percent of the variation in RR of CO_2 emissions was explained by clay content alone, whereas approximately 75% of the variation in RR of N_2O emissions was explained by clay content and temperature (Table 3).

Effect of environmental zone

The effect of the aggregated environmental zone (ENZ) on the response ratio of SOC concentration was not significant (Figure 2a). For GHG emissions, data were retrieved only for Atlantic and Mediterranean ENZs (Table 4). The RR for CO_2 for the Atlantic Zone was significantly larger than for the Mediterranean. For N_2O emissions, RR was greater for the Atlantic Zone compared with Mediterranean, although not significantly probably due to the considerable variability normally associated with this measurement.

Effect of clay content

Among different clay contents, a content >35% was found to be associated with significantly greater response ratios for SOC concentration compared with contents between 18 and 35% (Figure 2b). Data for GHG emissions were retrieved only for the clay contents <18 and 18–35% (Table 4). The RR for CO_2 for <18% clay content was sevenfold larger compared with that for the 18–35% clay content. For N_2O, the effect of clay was similar that on CO_2, being twice as much in soils with clay contents <18% compared with 18–35%. This difference, however, was not significant.

Effect of experiment duration

As the duration of the experiment increased, RR for SOC concentration also became larger (Figure 2c). The RR was statistically greater for experiments lasting >20 yr compared

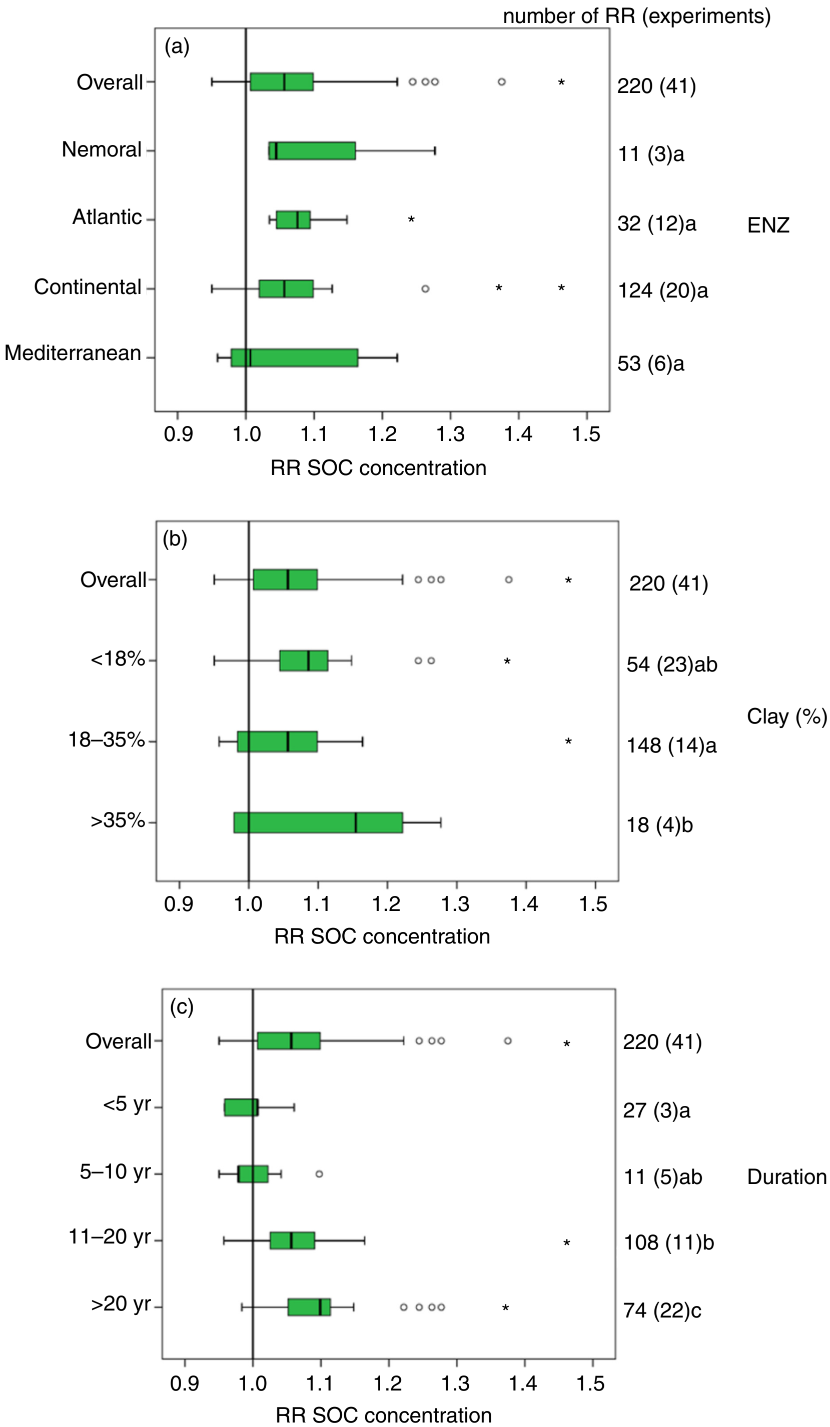

Figure 2 Response ratios (RRs) of SOC concentrations across (a) environmental zones (ENZs), (b) clay contents (%) and (c) experiment durations (years). The left vertical line of the box represents the first quartile, median is shown as a thick line and the right vertical line represents the third quartile. Horizontal bars show the minimum and maximum values. The (°) and (*) denote outliers. The figure is based on the original data on response ratios, without any weighting procedure. The numbers of RR (and experiments) are presented for each category along the *y*-axis. Different letters indicate significant differences according to Tukey's as a *post hoc* test ($P < 0.05$).

with the other duration periods. For CO_2 (Table 4), no distinction between duration groups could be detected because all the RRs were in the <5 yr group. For N_2O, RR was significantly larger in experiments lasting <5 yr compared with those of 11–20 yr duration. Note, however, that there was only one experiment in the 11–20 yr duration group.

Effect of experiment and crop residue type on RR for GHG emissions

We observed greater response ratios for CO_2 and N_2O emissions in laboratory experiments compared with field experiments (Table 4), except for N_2O emissions when cereal crop residues were incorporated. The RR was greater in

Table 4 Mean response ratios of GHG emissions in crop residue incorporation management practices compared with crop residue removal management practices in different aggregated environmental zones (ENZs), clay contents (%) and experiment durations (years)

	Cereal CO_2				Vegetative material CO_2			
	Mean	SD	n exp	n RR	Mean	SD	n exp	n RR
Overall								
Field	1.0a	0.08	3	17	1.7a	0.50	2	7
Laboratory	2.4b	0.46	3	15	9.2b	3.9	3	50
ENZ								
Atlantic								
Field	1.0	0.00	1	4	2.1	0.00	1	4
Laboratory	2.4	0.46	3	15	9.2	3.9	3	50
Mediterranean								
Field	1.0	0.09	2	13	1.1	0.00	1	3
Laboratory	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Clay %								
<18%								
Field	1.0	0.00	1	4	2.1	0.00	1	4
Laboratory	2.4	0.46	3	15	9.2	3.9	3	50
18–35%								
Field	1.0	0.09	2	13	1.1	0.00	1	3
Laboratory	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Duration								
<5 yr								
Field	1.0	0.08	3	17	1.7	0.50	2	7
Laboratory	2.4	0.46	3	15	9.2	3.9	3	50

	Cereal N_2O				Vegetative material N_2O			
	Mean	SD	n exp	n RR	Mean	SD	n exp	n RR
Overall								
Field	3.7a	3.60	4	30	1.9a	0.95	2	7
Laboratory	2.3a	2.30	3	15	21.4b	20.4	3	50
ENZ								
Atlantic								
Field	1.4	0.50	2	20	2.7	0.00	1	4
Laboratory	2.3	2.30	3	15	21.4	20.4	3	50
Mediterranean								
Field	8.4	2.34	2	10	0.9	0.00	1	3
Laboratory	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Clay %								
<18%								
Field	1.4	0.50	2	20	2.7	0.00	1	4
Laboratory	2.3	2.30	3	15	21.4	20.4	3	50
18–35%								
Field	8.4	2.34	2	10	0.9	0.00	1	3
Laboratory	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Duration								
<5 yr								
Field	5.5	3.67	3	18	1.9	0.95	2	7
Laboratory	2.3	2.30	3	15	21.4	20.4	3	50

Table 4 (continued)

	Cereal N_2O				Vegetative material N_2O			
	Mean	SD	n exp	n RR	Mean	SD	n exp	n RR
11–20 yr								
Field	1.0	0.00	1	12	N/A	N/A	N/A	N/A
Laboratory	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

The values have been calculated from average data from each experiment and were weighted based on the amount of response ratios calculated into the average. Different letters indicate significant differences according to Tukey's as a *post hoc* test ($P < 0.05$). SD, standard deviation; n exp, number of experiments; n RR, number of response ratios; RR, CO_2 or N_2O emissions in crop residue incorporation treatment/CO_2 or N_2O emissions in crop residue removal treatment; N/A, not available.

vegetative material crop residue incorporation experiments compared with cereal crop residue incorporation experiments (Table 4). In field experiments for N_2O emissions, however, the effect was the opposite.

Correlation between SOC concentration and crop yields

The mean RR for yield was 1.06 ± 0.15 ($n = 71$). This means that crop residue incorporation resulted in an average

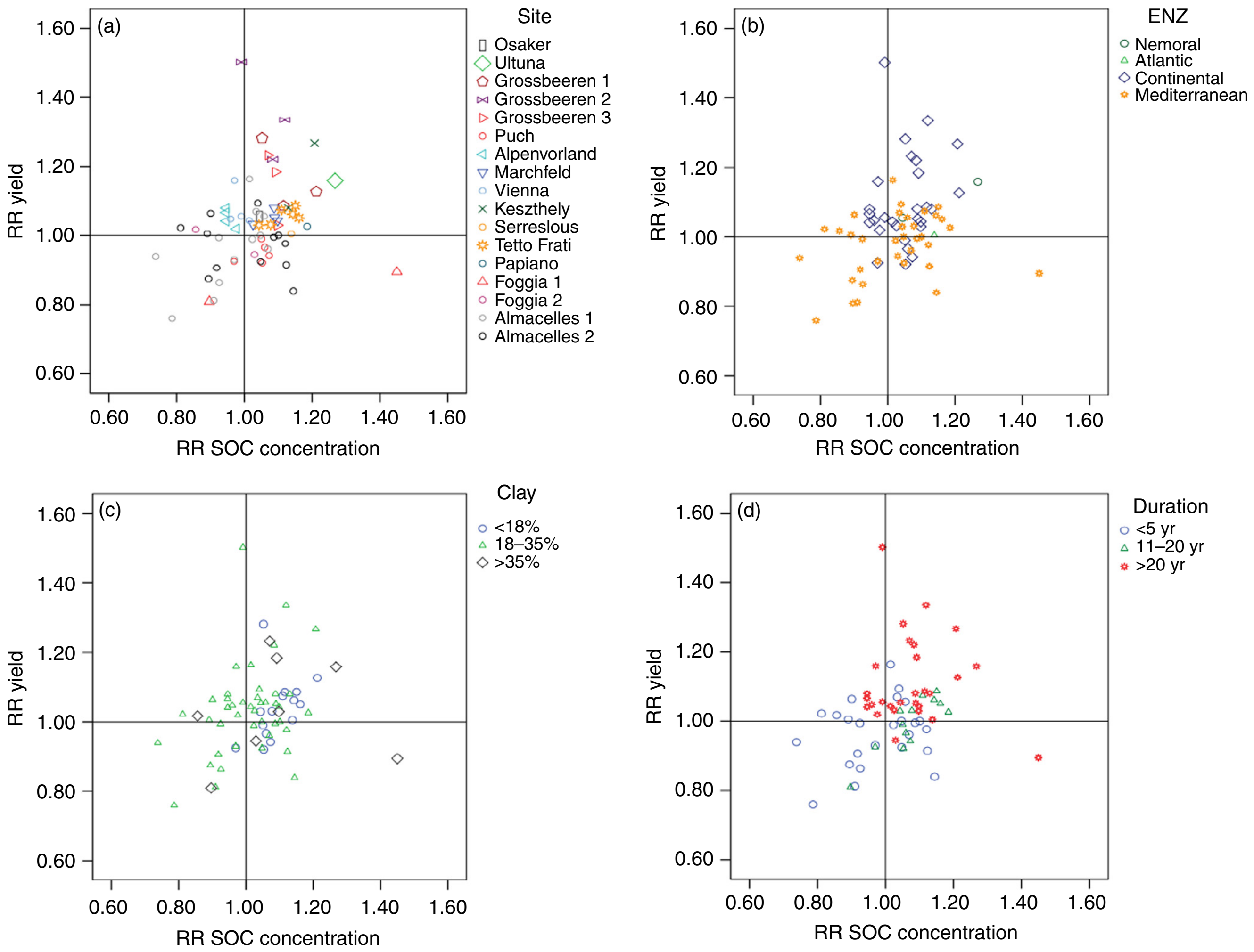

Figure 3 Correlation between RR for SOC concentration and crop yields (a) across the sites, (b) across the aggregated environmental zones, (c) across clay contents and (d) across experiment durations. The figure is based on the original data on response ratios, without any weighting procedure.

6% yield increase compared with crop residue removal. We expected to observe an increase in SOC together with an increase in yield due to a positive feedback between crop residue incorporation, nutrient availability, crop nutrient uptake rate and finally crop growth rate. From another perspective, larger crop yields result in more crop residue production, followed by greater SOC when these crop residues are incorporated. Unexpectedly, however, no significant correlation ($r = 0.02$, $P > 0.05$) was found between the RR of SOC concentration and the RR of yield. Differences between the studied sites (Figure 3a), ENZs (Figure 3b) and experiment durations were found (Figure 3d). No differences were detected between different clay content groups (Figure 3c). No effect of crop type was recorded, but yield data were available only for the crops wheat, barley and maize. The sites Kesthely, Grossbeeren 2 and Ultuna had the largest RRs in both SOC concentration and yield, whereas Almacelles 1 and 2 were among the sites with smallest RRs. As the experiment duration increased, the RRs for yields increased with the exception of Foggia 1 and Foggia 2, where RRs for yields were less than unity, even when the experiment had lasted for more than 20 yr.

Discussion

The results of this analysis demonstrate an increase in RR of SOC concentration following crop residue incorporation (Figure 2). The same has been demonstrated in previous meta-analyses for organic inputs (Lemke *et al*., 2010; Powlson *et al*., 2012), for example in organic farming (Gattinger *et al*., 2012; Aguilera *et al*., 2013). Incorporation of crop residues is one of the few methods applied by farmers to maintain SOC and to sustain soil functions (Powlson *et al*., 2008). This makes it a very important management tool. Even a small increase in SOC can improve soil physicochemical and biological properties and ecosystem services such as nutrient cycling and possible increases in yields (Loveland & Webb, 2003; Bhogal *et al*., 2009; Blanco-Canqui, 2013). A critical level of 2% SOC was thoroughly investigated by Loveland & Webb (2003); however, the authors concluded that a single value cannot be recommended with the evidence available but local conditions and relationships must be taken into account when desirable ranges for SOC are recommended.

The overall data for CO_2 and N_2O emissions were collected from both field and laboratory experiments as well as from experiments that incorporated cereals and vegetative materials. Thus, the standard deviation was high for these indicators, possibly due to spatial heterogeneity driven by variability in soil characteristics. With crop residue incorporation, CO_2 emissions will increase compared with crop residue removal due to more easily available C that enhances microbial activity (Meijide *et al*., 2010). In contrast, if crop residues are removed, they will be decomposed elsewhere, used as bedding and incorporated into farmyard manure or burned, releasing approximately the same amount of CO_2 (Blanco-Canqui, 2013). Thus, crop residue incorporation is not primarily a way to decrease CO_2 emissions and may not be beneficial for all soil ecosystem services such as carbon sequestration. To close the knowledge gap and to give better-informed recommendations to farmers, further field-scale research focusing on in situ carbon balance is required.

In the case of N_2O, emissions from crop residue incorporation are up to twelve times greater compared with crop residue removal. Emissions of N_2O occur both during the nitrification process and as a result of anaerobic denitrification. The latter process requires the presence of microbes capable of using nitrate. The increase of the RR for N_2O following crop residue incorporation in a study by Baggs *et al*. (2003) was explained by mineral N fertilizer application and an increased denitrification capacity stimulated by the added substrate. In our analysis, no distinct relationships were found with mineral N fertilizer application ($r = 0.08$, $P > 0.05$), most likely owing to the limited number of data. The soil respiration process may create anaerobic microsites in the soil and thereby increase N_2O emissions through denitrification (Garcia-Ruiz & Baggs, 2007; Abalos *et al*., 2013). Nonetheless, the N_2O emissions caused by the crop residues should be put in relation to the fact that not all removed crop residues are decomposed or burned with no N_2O emissions. Given that the global warming potential of N_2O is 298 on a 100-yr time scale, it is of importance to monitor these emissions in future studies and carry out analyses of gross global warming potential of crop residue incorporation versus removal, as has already been done in paddy soils (e.g. Shen *et al*., 2014).

Effect of environmental zone

The aggregated ENZ proved not to be a determining factor when RRs for SOC concentration, CO_2 and N_2O emissions were studied (Figure 2, Table 4). This is in contrast with concepts in which climate is directly and indirectly linked with carbon concentrations in soils (e.g. Ingram & Fernandes, 2001). One explanation may be that the aggregated ENZs in our study were too broad categories to capture the differences between different climates. ENZ is assigned based on several factors beyond climate, such as geomorphology, vegetation and fauna (Metzger *et al*., 2005). Given the large heterogeneity in these environmental factors across the experimental sites in this study, probably more data would have been required to detect significant differences between ENZs. In previous studies, temperature has been found to be one of the driving factors for both N_2O (Mutegi *et al*., 2010) and CO_2 emissions (Meijide *et al*., 2010). This was also supported by our multiple regressions, in the case of N_2O (Table 3).

Effect of clay content

Our results indicated larger RRs for SOC concentration for greater clay content (Figure 2b), probably because the clay fraction physically protects organic matter molecules from mineralization (Lal, 1997). SOM may be physically protected in the clay fraction of fine-textured soils by chemical bonds due to high surface activity (Six *et al*., 2000), thereby being inaccessible for microbial degradation (von Lützow *et al*., 2006). Nonetheless, the low clay content (<18%) soils also showed a positive SOC response to management changes (Cvetkov & Tajnsek, 2009). This may be explained by SOC being accumulated as POM in the sand fraction of these soils, and not additionally in the clay fraction, as has been shown in tropical soils (Feller & Beare, 1997; Chivenge *et al*., 2007). Furthermore, the initial SOC concentration of the soil may play a role in how much C is retained in the fine fraction (Poirier *et al*., 2013). The authors showed that soils with a small SOC concentration have a greater capacity to accumulate C in the fine fraction when large amounts of crop residues are added to the soil.

For GHG emissions, the number of experiments and RRs was too small to allow a representative analysis of differences between clay content groups. Velthof *et al*. (2002) compared sandy and clay soils under laboratory conditions and found the N_2O emissions to be much less in the latter than in the former. This is contrary to our analysis of field data on cereal crop residue incorporation (Table 4), but more measurements would be necessary before generalizations could be made. Indications of smaller RRs for N_2O emission in soils with a small content of clay are in accordance with a recent meta-analysis that confirmed the influence of texture on N_2O emissions (Chen *et al*., 2013). Soil texture may influence the response to crop residue incorporation through O_2 availability in soil microsites and its influence on denitrification (Chen *et al*., 2013).

Effect of experiment duration

The observed larger response ratios for SOC concentration in experiments of longer duration (Figure 2c) agree with previous studies (Körschens *et al*., 1998). For soils with clay contents <18%, there was a positive SOC response to changes in management 10 yr after its imposition (Cvetkov & Tajnsek, 2009) but it may be that SOC saturation in soils with a small clay content is reached faster than in those with a large content (>35%). As experiment duration increases, more interactions between clay minerals and SOC may take place (von Lützow *et al*., 2006); this is accompanied by a more marked accumulation of resistant crop residue C that is not mineralized (De Neve & Hofman, 2000), especially in soils without mechanical tillage (Six *et al*., 2000). Hence, the increase in SOC concentration has its limits and the accumulation rate becomes smaller when the soil system is close to a new equilibrium (Powlson *et al*., 2008).

For GHG emissions, the influence of the experiment duration was the opposite (Table 4), supporting a study by Chen *et al*. (2013). Those authors analysed experiment durations above and below 70 days and showed that the RR is initially higher, but as the duration increases, the RR of GHG emissions is also lower. Peak microbial activity when easily available organic inputs (crop residues) are added into the soil (Recous *et al*., 1995) may explain this response (Powlson *et al*., 2011).

Effect of experiment and crop residue type on RR for GHG emissions

The greater response ratios of N_2O emissions from incorporated vegetative material in laboratory experiments compared with those from field experiments (Table 4) are consistent with a meta-analysis that studied N_2O emissions following crop residue incorporation (Chen *et al*., 2013). Those authors explained the difference by the smaller size and subsequent increase of surface area of the crop residues in the laboratory experiments compared with field-scale applications. This applies to laboratory experiments in our analysis (Velthof *et al*., 2002; Garcia-Ruiz & Baggs, 2007; Cayuela *et al*., 2014), compared to the field experiments (Baggs *et al*., 2003; Mutegi *et al*., 2010; Abalos *et al*., 2013; Sanz-Cobena *et al*., 2014). Moreover, under laboratory conditions, moisture and temperature are stable and optimized for microbial activity, thus promoting higher emissions compared to field experiments (Chen *et al*., 2013).

Previous studies show that N_2O emissions decrease at a higher C/N ratio of the residues (Alexander, 1977; Shan & Yan, 2013). This is in line with the observed higher RR of GHG emissions (Table 4) in vegetative material crop residue incorporation experiments compared with cereal crop residue incorporation experiments in our study. This may be explained by immobilization of N with increasing C/N ratio of the crop residues (Abalos *et al*., 2013). The oxidation rate is greater immediately after the incorporation of vegetative material (compared with cereal residues) due to quick decomposition, thus possibly promoting larger denitrification rates (Nicolardot *et al*., 2001; Rizhiya *et al*., 2011). Greater GHG emissions from low-C/N-ratio crop residue incorporation were observed in individual studies under field conditions in our analysis (e.g. Baggs *et al*., 2000, 2003). This can be explained by the availability of N being greater, first for nitrification and then for denitrification, when the C/N ratio of incorporated crop residue is small (Baggs *et al*., 2003). Garcia-Ruiz & Baggs (2007), however, stated that more knowledge on the interactions between organic and inorganic N sources and compounds released from the crop residues is required before drawing conclusions on how to reduce GHG emissions following crop residue incorporation.

One additional explanation for the RR of GHG emissions may be the cultivation technique, which affects the nutrient supply to microorganisms and the aeration (Baggs *et al.*, 2003; Mutegi *et al.*, 2010). However, soil tillage was not in the scope of this study. Another potential factor is N fertilizer application, which increased GHG emissions in several studies (e.g. Garcia-Ruiz & Baggs, 2007; Meijide *et al.*, 2010; Sanz-Cobena *et al.*, 2014). Nevertheless, our analysis did not reveal any significant correlations between N_2O emissions and addition of mineral N fertilizer. This may be due to limited data accessibility and differences in the set-up of the experiments we investigated. The variation observed between ENZs, clay content groups and experiment durations within experiment types and crop residue types most likely reflected differences between experiments and not between the categories. More data from long-term field experiments are required to enable a study of such relationships.

Correlations between crop yields and SOC concentrations

The slight positive influence of crop residue incorporation on crop yield (Figure 3a) contradicts previous studies reporting yield decreases (Swan *et al.*, 1994; Nicholson *et al.*, 1997), but agrees with Wilhelm *et al.* (2004). The positive influence of crop residue incorporation may be explained by the increase in SOC and the experiment duration (Figure 3a,d). Crop residues act as a continuous source of soil nutrients and SOM (Liu *et al.*, 2014), which improves soil functioning (Bhogal *et al.*, 2009) and thereby yields. Thus, a positive feedback, initiated by incorporation of crop residues, occurs. In the case of the Foggia experiment (Figure 3a), the incorporation of crop residues lowered yield because of the poor mineralization and strong N immobilization due to arid climate and the low soil N status (Maiorana, 1998). Mineral N fertilizer application did not increase yields at Almacelles even though SOC concentrations were sufficient, possibly due to the short duration of the experiment and the arid climate (Biau *et al.*, 2013).

Possible improvements of the data set for future analyses

Long-term experiments with data on SOC concentrations and GHG emissions from the same experiments are lacking in our data set. To reach sustainable agricultural management with a positive soil carbon budget, both SOC and GHG emissions should be taken into account (Ingram & Fernandes, 2001; Lal, 2013). This calls for long-term field experiments to study these interactions and possible trade-offs between management practices (Körschens, 2006). The present study was based on measurements from the topsoil (<30 cm), in the future, it would be important to investigate SOC concentrations also in the deeper soil layers (Aguilera *et al.*, 2013; Lal, 2013).

Conclusions

This analysis indicates that the impacts of crop residue incorporation on SOC concentration are positive, but the CO_2 and N_2O emissions are increased. Even a small decrease in SOC may have detrimental effects on other soil properties such as aggregate stability. Thus, maintaining or even increasing SOC levels is crucial for agricultural soils. We show that long-term crop residue incorporation may increase crop yields. A win-win scenario between yield and SOC is for crop residue incorporation over a longer term (>20 yr) under a continental climate. Data availability from field experiments on GHG emissions is still scarce, and the data do not allow for selection of win-win scenarios for these parameters. Thus, more long-term field studies are needed to better assess the CO_2 and N_2O emissions following crop residue incorporation, specifically from the same studies in which SOC is measured. We conclude that crop residue incorporation is an important management practice to maintain SOC concentrations and to sustain soil functioning, but that its influence on GHG emissions should be considered. GHG emissions should be measured in ongoing long-term field experiments to more accurately calculate trade-offs such as in situ SOC and GHG balances following crop residue management in agricultural systems.

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