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

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Abstract

Soil organic matter (SOM) improves soil physicochemical and biological properties, and the sequestration of 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 influences of environmental zones (ENZs), clay content and experiment duration on the RRs were investigated. We also studied how RRs of SOC and crop yields were correlated. A total of 718 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 to soils with clay contents between 18 and 35 %. As the experiment progressed, RR for SOC concentration and stock increased. For N_2O emissions, RR was significantly higher in experiments with a duration <5 years compared to 11-20 years. No significant correlations were found between RR for SOC concentration and yields, but differences between sites and study durations were detected. We suggest a win-win scenario to be crop residue incorporation for a long duration in a continental climate, whereas the worst-case scenario involves crop residue incorporation over the short term in the Mediterranean, especially with vegetative material. 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 (CO_2), nitrous oxide (N_2O), soil organic carbon, response ratio, crop residue management, climate change

1. Introduction

Soil organic matter 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 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 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 low SOC concentrations (Aguilera et al., 2013), and areas where stockless croplands predominate (Kismányoky and Tóth, 2010; Spiegel et al., 2010b), could benefit from this management practice. Nonetheless, crop residue incorporation increases the SOC concentrations and stocks less than does farmyard manure (Cvetkov et al., 2010) or slurry (Triberti et al., 2008). For 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 lack of studies focusing on both SOC and GHG emissions (Ingram and Ferdandes, 2001) calls for an analysis of European results.

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. Studies with both SOC and GHG emissions are still missing. An analysis of European 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 an important factor for analysing the effects of crop residue incorporation on SOC concentration and stock, as well as on GHG emissions (CO_2, N_2O)?
ii) Does the effect of crop residue incorporation change with a change in clay content?
iii) Does the duration of the experiment influence the response ratios of SOC and GHG emissions following crop residue incorporation?
iv) Do the experimental setup and crop residue type affect the RR of GHG emission following crop residue incorporation?
v) Are RRs for SOC concentrations and yields correlated?

SOC stocks were analysed separately in order to confirm the results emerging from SOC concentrations. We hypothesised that the response ratios of SOC increase the most in the Nemoral ENZ due to low temperatures, particularly in high clay content soils due to interactions between SOC and clay minerals, and furthermore increase with time. The response ratios of GHG emissions were expected to be lowest in the Nemoral ENZ, and to decrease with time. We expected the response ratios of GHG emissions to be higher in laboratory versus field experiments due to more favourable conditions for the microorganisms, such as optimal soil water content. The RR of GHG emissions were expected to be higher with incorporation of low-C/N-ratio crop residues (hereafter referred to as "vegetative material" such as sugar beet, potato or leafy greens compared to 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.

2. Materials and methods

2.1 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 718 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 were published in national technical journals and conference proceedings. The publications report on measurements of SOC concentration, SOC stock, 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 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 with similar fertilization 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).

2.2 Data preparation

If SOC concentrations but no bulk density (BD) or SOC stock data were reported, the latter two properties were estimated according to the formulas mentioned below to increase the number of studies. For 26 experiments in which BD was not available, it was calculated according to Ruehlmann and Körschens (2009):

$$BD = (2.684-140.934*0.008)*EXP(-0.008*SOC)$$

where BD is the standardised bulk density (Mg m^{-3}), 2.684 is the mean density of mineral soil particles (Mg m^{-3}) as estimated by Rühlmann et al. (2006), 140.934 is the fitted coefficient, 0.008 is the coefficient for arable soils, and SOC is the concentration of soil organic carbon (g kg^{-1}).

SOC stock (Mg C ha^{-1}) in the corresponding soil layer was calculated as:

$$SOC\ stock = SOC*D*BD*10$$

where SOC is the concentration of soil organic carbon (g kg^{-1}), D is the thickness of the soil layer (m), and BD is the soil bulk density (Mg m^{-3}).

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

$$RR = property_I/property_R$$

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

2.3 Data aggregation

In some cases it was possible to derive more than one comparison from an experiment, e.g. 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.

2.4 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, SOC stock 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, clay content, duration of the experiment were tested) on RR of SOC concentration, SOC stock, 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 correlation coefficients.

3. Results

Crop residue incorporation increased the SOC concentration and SOC on average by 7% (Figure 1), whereas CO_2 emissions were increased almost six fold and N_2O emissions more than twelve 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). For SOC stock, both clay content and experiment duration affected the response ratio and explained 22% of the variation (Table 3). 98% 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).

3.1 Effect of environmental zone

The effect of the aggregated ENZ on the response ratio of SOC concentration was not significant (Figure 2A). In contrast, the response ratio of the SOC stock was 4% lower in the Mediterranean versus the Continental Zone (Figure 2B). 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 higher than for the Mediterranean. For N_2O emissions, RR was higher for the Atlantic Zone compared to Mediterranean, although not significantly due to the high variability normally associated with this measurement.

3.2 Effect of clay content

Among different clay contents, a content >35 % was found to be associated with significantly higher response ratios for SOC concentration compared to contents between 18 and 35 % (Figure 2C). The same was observed for SOC stocks (Figure 2D). 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 seven fold higher compared to 18-35 % clay content. For N_2O, the effect of clay was similar as for CO_2, being twice as high in soils with clay contents <18 % compared to 18-35 %. This difference, however, was not significant.

3.3 Effect of experiment duration

As the duration of the experiment rose, RR for SOC concentration increased (Figure 2E). The RR was statistically higher for experiments lasting >20 years compared to the other duration groups. Also, the RR for SOC stock was dependent on experiment duration (Figure 2F), being significantly lower in experiments <5 years compared to the duration groups 11-20 and >20 years. For CO_2 (Table 4), no distinction between duration groups could be detected because all the RRs were in the <5 years group. For N_2O, RR was significantly higher in experiments lasting <5 years compared to the 11-20 years duration. Note, however, that there was only one experiment in the 11-20 years duration group.

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

We observed higher response ratios for CO_2 and N_2O emissions in laboratory experiments compared to field experiments (Table 4), except for N_2O emissions when cereal crop residues were incorporated. The RR was higher in vegetative material crop residue incorporation experiments compared to cereal crop residue incorporation experiments (Table 4). In field experiments for N_2O emissions, however, the effect was opposite. This was a result of lower RR in vegetative material crop residue incorporation experiments compared to cereal crop residues in the Mediterranean environmental zone with 18-35 % clay content and less than five years experiment duration (Table 4).

3.5 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 6 % yield increase compared to 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, higher crop yield means higher crop residue production, followed by higher 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 highest RRs in both SOC concentration and yield, whereas Almacelles 1 and 2 were among the sites with lowest RRs. As the experiment duration increased, the RRs increased with the exception of Foggia 1 and Foggia 2, where RR for yields was below one even when the experiment lasted more than twenty years.

4. Discussion

The results of this analysis demonstrate an increase in RR of SOC concentration and stock following crop residue incorporation (Figure 2) representing an additional annual C input. The same has been demonstrated in previous meta-analyses for organic inputs (Lemke et al., 2010; Powlson et al., 2012), e.g. 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 and Webb, 2003; Bhogal et al., 2009; Blanco-Canqui, 2013).

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 to 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. In order 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 higher compared to 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 nitrates. 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 fertilization and an increased denitrification capacity stimulated by the added substrate. In our analysis, no distinct relationships were found with mineral N fertilisation ($r=0.08$, $p>0.05$), most likely due 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 and 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.

4.1 Effect of environmental zone

The aggregated ENZ proved not to be a determining factor when RRs for SOC concentration, SOC stock, 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 are 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).

4.2 Effect of clay content

Our results indicated higher RR for SOC concentration and stock with higher clay content (Figure 2C, D), 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 and 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 and Beare, 1997; Chivence 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 low-SOC-concentration soils have a greater capacity to accumulate C in the fine fraction when high 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 lower in the latter than in the former. This is supported by our analysis of field data on cereal crop residue incorporation (Table 4), but more measurements would be necessary before generalisations could be made. Indications of lower RR of N_2O emission in lower-clay-content soils 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).

4.3 Effect of experiment duration

The observed higher response ratios for SOC concentration and stock for longer experiment durations (Figure 2) agree with previous studies (Körschens et al., 1998). The low clay-content (<18 %) soils showed a positive SOC response to management changes after ten years of management difference (Cvetkov and Tajnsek, 2009), but it may be that SOC saturation in soils with low clay content is reached faster than in high 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 mineralised (De Neve and 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).

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

The higher response ratios of N_2O emissions in vegetative material laboratory experiments compared to field experiments (Table 4) agree 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 to field-scale applications. This applies to laboratory experiments in our analysis (Velthof et al., 2002; Garcia-Ruiz & Baggs, 2007; Cayuela et al., 2013), 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 optimised 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 and Yan, 2013). This is in line with the observed higher RR of GHG emissions (Table 4) in vegetative material crop residue incorporation experiments compared to cereal crop residue incorporation experiments in our study. This may be explained by immobilisation of N with increasing C/N ratio of the crop residues (Abalos et al., 2013). The oxidation rate is higher immediately after the incorporation of vegetative material (versus cereal residues) due to quick decomposition, thus possibly promoting higher denitrification rates (Nicolardot et al., 2001; Rizhiya et al., 2011). Higher 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 higher availability of N first for nitrification and then for denitrification when the C/N ratio of incorporated crop residue is low (Baggs et al., 2003). Garcia-Ruiz and 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 fertilisation, which increased GHG emissions in several studies (e.g. Garcia-Ruiz and 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 mineral N fertilisation. This may be due to limited data accessibility and differences in the set-up of the experiments we investigated. The differences 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.

4.5 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 soil organic matter (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 mineralisation and strong N immobilisation due to arid climate and the low soil N status (Maiorana, 1998). Mineral N fertilization 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).

4.6 Possible improvements of the data set for future analyses

Long-term experiments with data on SOC concentrations, stocks and GHG emissions from the same experiment are lacking in our dataset. To reach sustainable agricultural management with a positive soil carbon budget, both SOC and GHG emissions should be taken into account (Ingram & Ferdandes, 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 and stocks also in the deeper soil layers (Aguilera et al., 2013; Lal, 2013).

5. Conclusions

This analysis indicates that the impacts of crop residue incorporation on SOC concentration and stock 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 crop residue incorporation over the longer term (>20 years) in a continental climate. The worst-case scenario would occur with short-term crop residue incorporation, especially with vegetative material, in a Mediterranean setting. Data availability from field experiments on GHG emissions is still scarce, and the data do not allow for selection of win-win and worst-case 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 stocks and to sustain soil functioning, but that its influence on GHG emissions should be considered. GHG emissions should be measured in on-going 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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Figures

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

Figure 2 Response ratios (RRs) in A,C,E) SOC concentrations, and B,D,F) SOC stocks across A,B) environmental zones (ENZs), C,D) clay contents (%), and E,F) 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 ($p<0.05$).

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

Tables

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Table 4 Mean response ratios of GHG emissions in crop reside incorporation management practice compared to crop residue removal management practice in different environmental zones (ENZ), clay contents (%), and experiment durations (years). 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.

Table 1 Summary description of sites included in the analysis.

Experiment Nr	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, 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; 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; 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; 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; MLUV, 2009
20	Grossbeeren 2	Germany	52°21´N 13°18´E	CON	1972	sandy loam	Rühlmann & Ruppel, 2005; Rühlmann, 2006; MLUV, 2009
21	Grossbeeren 3	Germany	52°21´N 13°18´E	CON	1972	silt	Rühlmann & Ruppel, 2005; Rühlmann, 2006; 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	Kismanyoky & 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; 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; Lubet et al., 1993
38	Tetto Frati	Italy	44°53'N 07°41'E	MDM	1992	loam	Grignani et al., 2007; Bertora et al., 2009; 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; Perucci et al., 1997
41	Foggia 1	Italy	41°27´N 15°32´E	MDN	1977	clay	Maiorana, 1998; Maiorana et al. 2004
42	Foggia 2	Italy	41°27´N 15°32´E	MDN	1990	clay	Maiorana, 1998; 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; 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., 2013
50	Wye Estate	UK	51°10´N 00°56´E	ATC	1999	silty loam	Garcia-Ruiz & Baggs, 2007

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[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.

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 years	5-10 years	11-20 years	>20 years

[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[a]	95% CI[b]	T	P
Intercept	0.008	0.004	0.001-0.016	2.125	0.035
Duration	0.001	0.0002	0.0006-0.0012	5.864	<0.0001

LOG RR of SOC stock

	R^2	F	P	n	
Model	0.218	33.405	<0.0001	243	
Variables	Coefficient	SE	95% CI	T	P
Intercept	0.046	0.005	0.035-0.057	8.458	<0.0001
Clay content	-0.002	0.0002	-0.002-(-)0.001	-6.61	<0.0001
Duration	0.001	0.0001	0.0005-0.001	5.67	<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	0.469-0.159	40.608	<0.0001
Clay content	-0.018	0.001	-0.019-(-)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	0.048-1.126	2.212	0.034
Clay content	0.098	0.017	0.068-0.133	5.721	<0.0001
Temperature	-0.185	0.052	-0.289-(-)0.080	-3.579	0.001

[a] SE, standard error

[b] CI, confidence interval

Table 4 Mean response ratios of GHG emissions in crop residue incorporation management practices compared to crop residue removal management practices in different aggregated environmental zones (ENZs), clay contents (%), and experiment durations (years). 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 ($p<0.05$).

		Cereal				Vegetative material			
		CO_2				CO_2			
		Mean	SD[a]	n exp[b]	n RR[c]	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 years	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				Vegetative material			

		N_2O				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 years	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
11-20 years	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

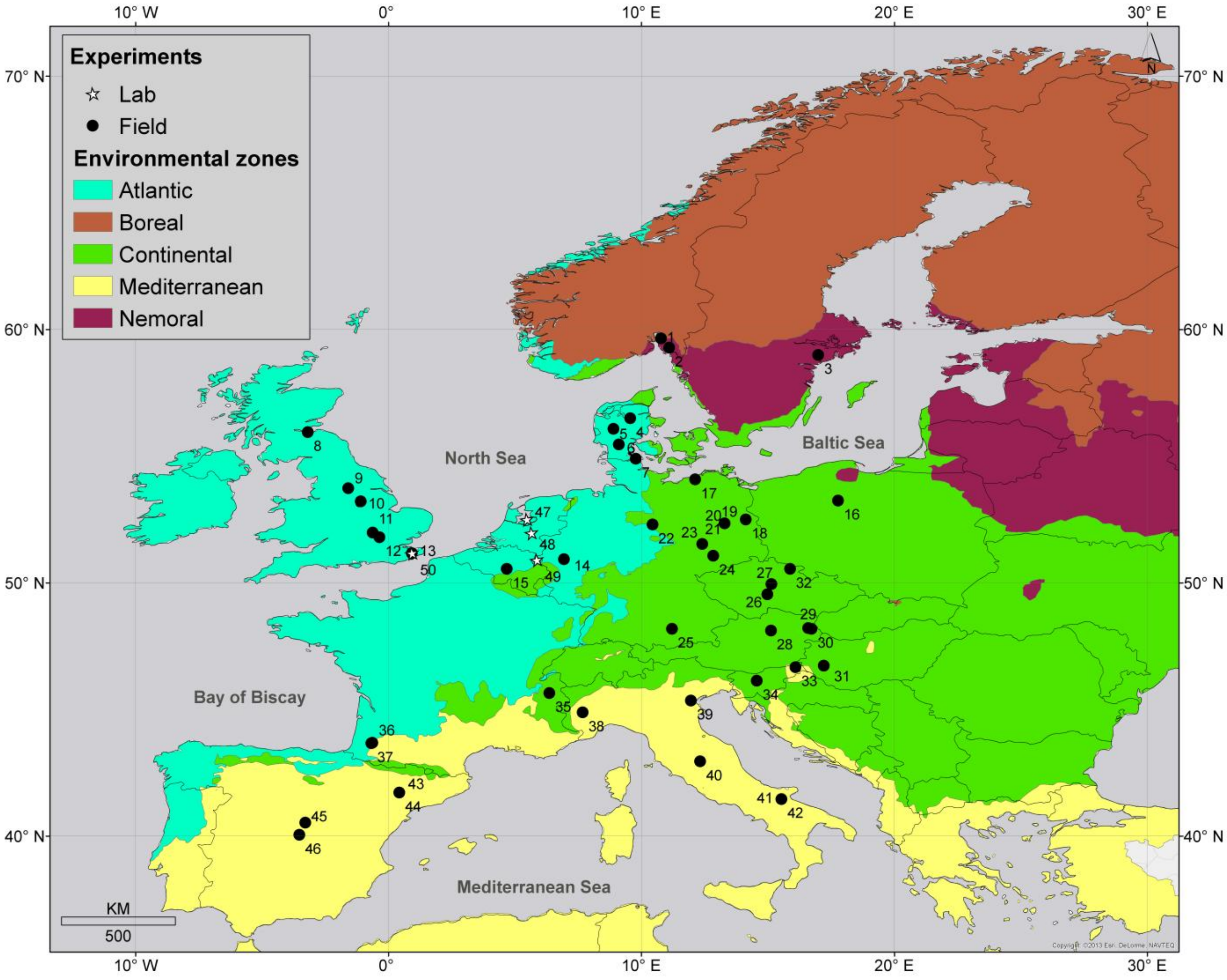
[a] SD, standard deviation.

[b] n exp, number of experiments.

[c] 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.

Figure 1.


Experiments
☆ Lab
● Field
Environmental zones
🟦 Atlantic
🟫 Boreal
🟩 Continental
🟨 Mediterranean
🟪 Nemoral
North Sea
Baltic Sea
Bay of Biscay
Mediterranean Sea
KM
500
N
10° W
0°
10° E
20° E
30° E
70° N
60° N
50° N
40° N
1
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3
4
5
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Figure 2.

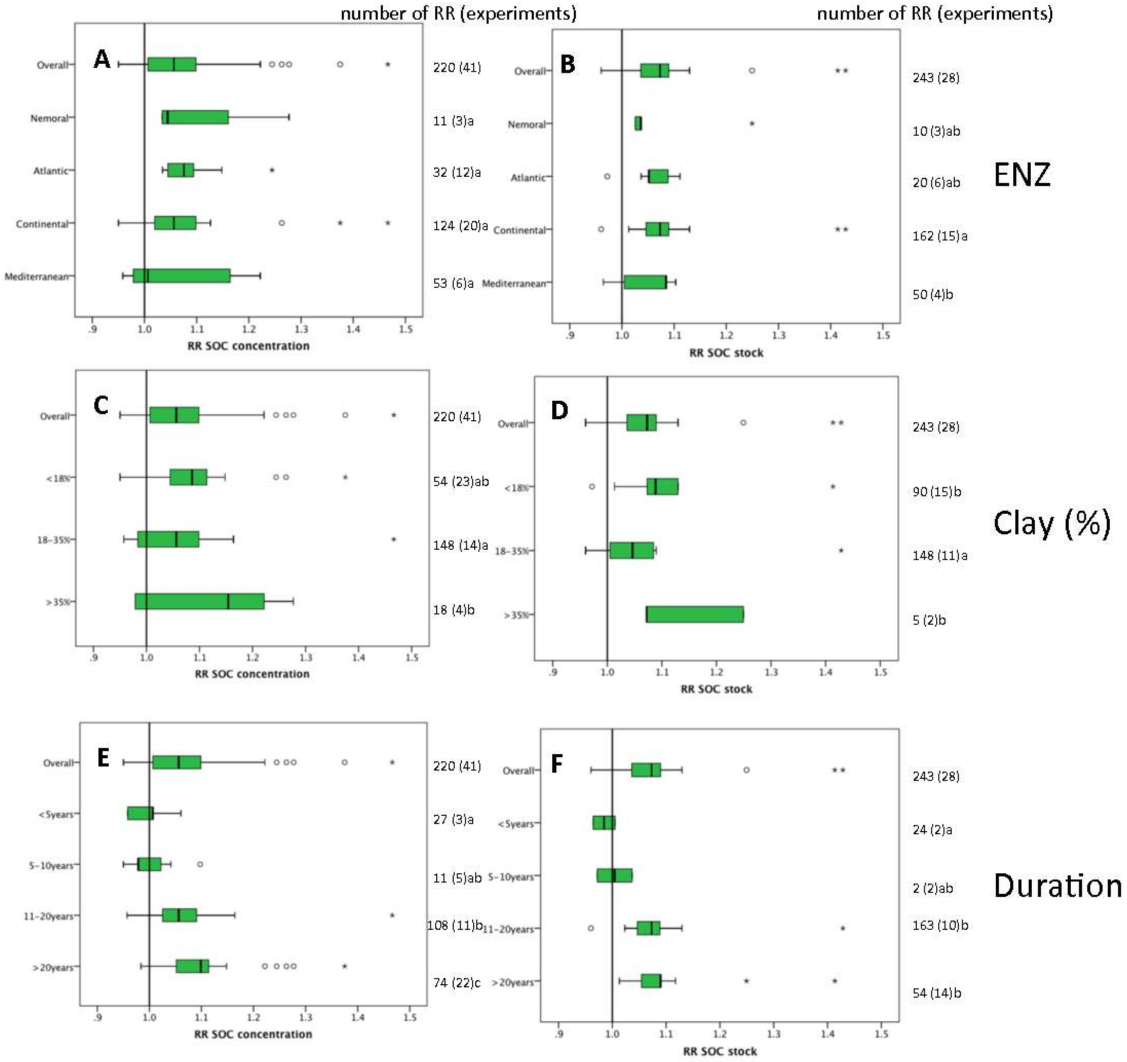
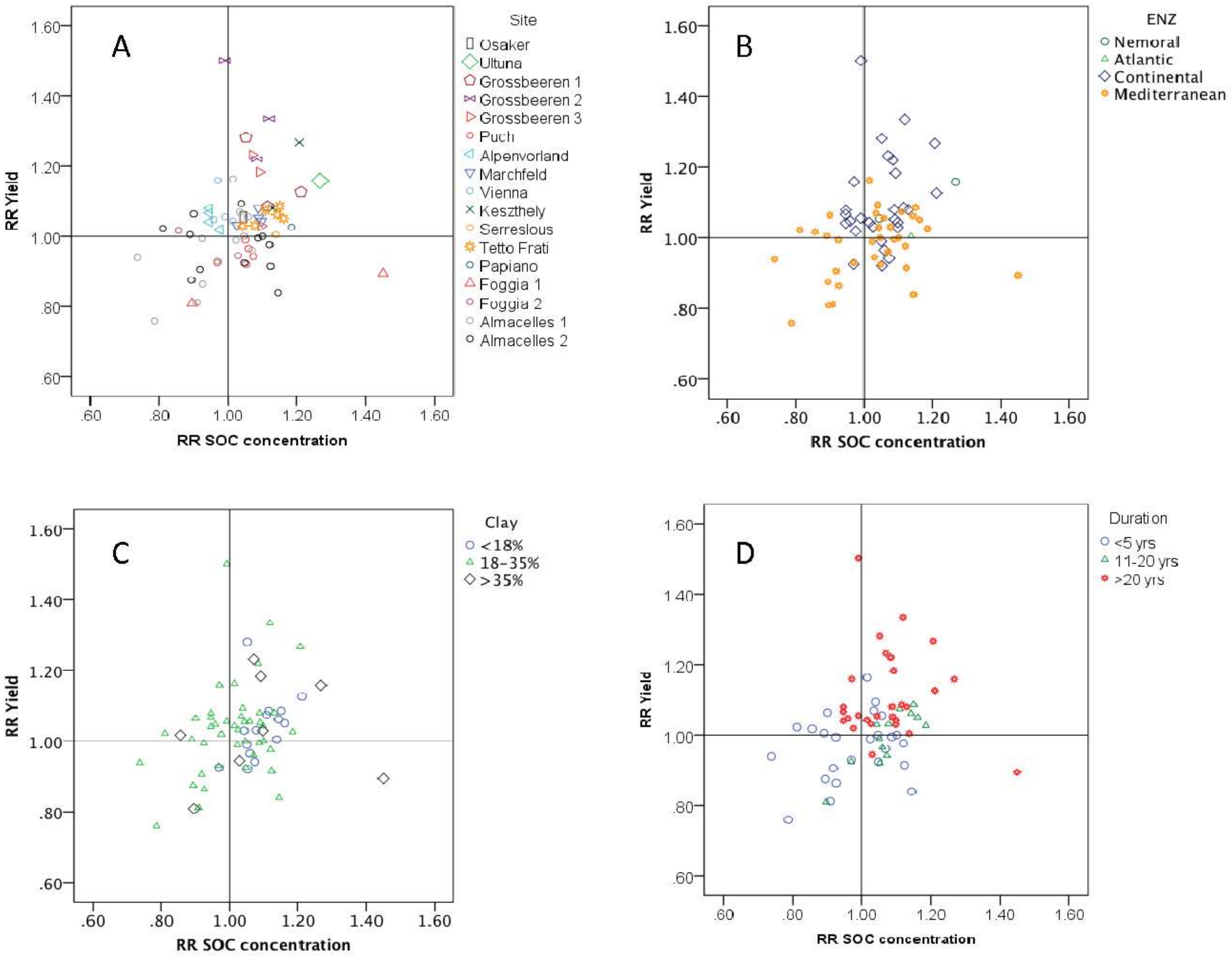

number of RR (experiments)
number of RR (experiments)
A
Overall
Nemoral
Atlantic
Continental
Mediterranean
220 (41)
11 (3)a
32 (12)a
124 (20)a
53 (6)a
.9
1.0
1.1
1.2
1.3
1.4
1.5
RR SOC concentration
B
Overall
Nemoral
Atlantic
Continental
Mediterranean
243 (28)
10 (3)ab
20 (6)ab
162 (15)a
50 (4)b
RR SOC stock
ENZ
C
Overall
<18%
18-35%
>35%
220 (41)
54 (23)ab
148 (14)a
18 (4)b
RR SOC concentration
D
Overall
<18%
18-35%
>35%
243 (28)
90 (15)b
148 (11)a
5 (2)b
RR SOC stock
Clay (%)
E
Overall
<5years
5-10years
11-20years
>20years
220 (41)
27 (3)a
11 (5)ab
108 (11)b
74 (22)c
RR SOC concentration
F
Overall
<5years
5-10years
11-20years
>20years
243 (28)
24 (2)a
2 (2)ab
163 (10)b
54 (14)b
RR SOC stock
Duration

Figure 3


A
RR Yield
RR SOC concentration
1.60
1.40
1.20
1.00
.80
.60
Site
Osaker
Ultuna
Grossbeeren 1
Grossbeeren 2
Grossbeeren 3
Puch
Alpenvorland
Marchfeld
Vienna
Keszthely
Serreslous
Tetto Frati
Papiano
Foggia 1
Foggia 2
Almacelles 1
Almacelles 2
B
ENZ
Nemoral
Atlantic
Continental
Mediterranean
C
Clay
<18%
18-35%
>35%
D
Duration
<5 yrs
11-20 yrs
>20 yrs