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

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29 **Abstract**

30 Soil organic matter (SOM) improves soil physicochemical and biological properties, and the  
31 sequestration of SOM may mitigate climate change. Soil organic carbon (SOC) often decreases in  
32 intensive cropping systems. Incorporation of crop residues (CR) may be a sustainable  
33 management practice to maintain the SOC levels and to increase soil fertility. This study  
34 quantifies the effects of CR incorporation on SOC and greenhouse gas (GHG) emissions (CO<sub>2</sub> and  
35 N<sub>2</sub>O) in Europe using data from long-term experiments. Response ratios (RRs) for SOC and GHG  
36 emissions were calculated between CR incorporation and removal. The influences of  
37 environmental zones (ENZs), clay content and experiment duration on the RRs were  
38 investigated. We also studied how RRs of SOC and crop yields were correlated. A total of 718 RRs  
39 were derived from 39 publications. The SOC increased by 7 % following CR incorporation. In  
40 contrast, in a subsample of cases, CO<sub>2</sub> emissions were six times and N<sub>2</sub>O emissions 12 times  
41 higher following CR incorporation. The ENZ had no significant influence on RRs. For SOC  
42 concentration, soils with a clay content >35 % showed 8 % higher RRs compared to soils with  
43 clay contents between 18 and 35 %. As the experiment progressed, RR for SOC concentration  
44 and stock increased. For N<sub>2</sub>O emissions, RR was significantly higher in experiments with a  
45 duration <5 years compared to 11-20 years. No significant correlations were found between RR  
46 for SOC concentration and yields, but differences between sites and study durations were  
47 detected. We suggest a win-win scenario to be crop residue incorporation for a long duration in  
48 a continental climate, whereas the worst-case scenario involves crop residue incorporation over  
49 the short term in the Mediterranean, especially with vegetative material. We conclude that CR  
50 incorporation is important for maintaining SOC, but its influence on GHG emissions should be  
51 taken into account as well.

52

53 Keywords: carbon dioxide (CO<sub>2</sub>), nitrous oxide (N<sub>2</sub>O), soil organic carbon, response ratio, crop  
54 residue management, climate change

## 55 **1. Introduction**

56 Soil organic matter improves soil physical (e.g. increased aggregate stability), chemical (e.g.  
57 cation exchange capacity) and biological (e.g. biodiversity, earthworms) properties, and it  
58 mitigates climate change by sequestering carbon in soils (Lal, 2013). Currently, as much as 25-  
59 75 % of the SOC in the world's agricultural soils may have been lost due to intensive agricultural  
60 practices (Lal, 2013), and about 45 % of European soils exhibit low organic matter contents  
61 (European Commission, 2006). The decline of OM is one of the major threats to soils described  
62 by the European Commission (European Commission, 2006).

63 Globally, approximately four billion tons of crop residues are produced (Chen et al., 2013).  
64 Removal of crop residues has a negative effect on SOC, but an estimated 25-50 % of crop  
65 residues could be harvested without threatening soil functions (Blanco-Canqui, 2013).  
66 Harvesting crop residues may be beneficial for farmers because residues can be used as  
67 livestock bedding, sold or thermally utilized. Harvesting residues also fits reduced or no-tillage  
68 farming operations because the soil will be less disturbed due to no ploughing of crop residues  
69 into the soil. Incorporation of crop residues may be a sustainable and cost-effective management  
70 practice to maintain the ecosystem services provided by soils, the SOC levels and to increase soil  
71 fertility in European agricultural soils (Perucci et al., 1997; Powlson et al., 2008). In particular,  
72 Mediterranean soils with low SOC concentrations (Aguilera et al., 2013), and areas where  
73 stockless croplands predominate (Kismányoky and Tóth, 2010; Spiegel et al., 2010b), could  
74 benefit from this management practice. Nonetheless, crop residue incorporation increases the  
75 SOC concentrations and stocks less than does farmyard manure (Cvetkov et al., 2010) or slurry  
76 (Triberti et al., 2008). For GHG emissions, both positive and negative effects have been observed  
77 following crop residue incorporation (e.g. Abalos et al., 2013). Emissions of CO<sub>2</sub> indicate  
78 heterotrophic microbial activity and particularly mineralization (Baggs et al., 2003), whereas  
79 N<sub>2</sub>O emissions indicate both nitrification and denitrification processes (Chen et al., 2013). The  
80 lack of studies focusing on both SOC and GHG emissions (Ingram and Ferdandes, 2001) calls for  
81 an analysis of European results.

82 The response of soil properties to management practices may depend on various factors such as  
83 soil temperature and soil moisture content, soil clay content (Körschens, 2006; Chen et al., 2013)  
84 or duration of the experiment (Smith et al., 2012; Chen et al., 2013). Metzger et al. (2005)  
85 presented a stratification of environmental zones (ENZs) in Europe, which is based on climate,  
86 geology and soils, geomorphology, vegetation and fauna. It can be used to compare the response  
87 of soil to management practices across Europe (Jongman et al., 2006). In their meta-analysis,  
88 Chen et al. (2013) showed that the clay content was a good predictor for N<sub>2</sub>O emissions  
89 following crop residue incorporation. Especially in the case of soil processes, the experiment  
90 duration improves the accuracy of data. Accordingly, long-term experiments are very important  
91 when assessing the impact of a management practice on soil (Körschens, 2006). Effects of crop  
92 residue incorporation on SOC and GHG emissions have been studied across the world (Chen et  
93 al., 2013, Liu et al., 2014), but the results differ due to the wide range of systems inherent in a  
94 global coverage. Studies with both SOC and GHG emissions are still missing. An analysis of  
95 European long-term experiments (LTEs) helps integrate current knowledge in Europe and  
96 provides guidance for policy development.

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

- 100 i) Are environmental zones an important factor for analysing the effects of crop residue  
101 incorporation on SOC concentration and stock, as well as on GHG emissions (CO<sub>2</sub>,  
102 N<sub>2</sub>O)?
- 103 ii) Does the effect of crop residue incorporation change with a change in clay content?
- 104 iii) Does the duration of the experiment influence the response ratios of SOC and GHG  
105 emissions following crop residue incorporation?
- 106 iv) Do the experimental setup and crop residue type affect the RR of GHG emission  
107 following crop residue incorporation?
- 108 v) Are RRs for SOC concentrations and yields correlated?

109 SOC stocks were analysed separately in order to confirm the results emerging from SOC  
110 concentrations. We hypothesised that the response ratios of SOC increase the most in the  
111 Nemoral ENZ due to low temperatures, particularly in high clay content soils due to  
112 interactions between SOC and clay minerals, and furthermore increase with time. The  
113 response ratios of GHG emissions were expected to be lowest in the Nemoral ENZ, and to  
114 decrease with time. We expected the response ratios of GHG emissions to be higher in  
115 laboratory versus field experiments due to more favourable conditions for the  
116 microorganisms, such as optimal soil water content. The RR of GHG emissions were expected  
117 to be higher with incorporation of low-C/N-ratio crop residues (hereafter referred to as  
118 “vegetative material” such as sugar beet, potato or leafy greens compared to high-C/N-ratio  
119 crop residues, hereafter referred to as “cereal” such as barley, wheat or maize residue  
120 incorporation). Further, we expected to observe a positive correlation between yields and  
121 SOC concentrations, as higher yields would result in more residues and greater accumulation  
122 of SOC.

## 123 **2. Materials and methods**

### 124 *2.1 Data sources*

125 A detailed literature review was conducted concerning scientific publications that had reported  
126 on long-term agricultural experiments in Europe. This yielded a total of 718 response ratios  
127 from 39 publications (Table 1), 50 experiments in 15 countries. An online database was created,  
128 which included 46 field experiments and four laboratory experiments that covered 10 European  
129 Environmental Zones (ENZs), as defined by Metzger et al. (2005), and four aggregated ENZs  
130 (Figure 1, Table 2). Most of the data were published in peer-reviewed scientific journals, while a  
131 smaller fraction were published in national technical journals and conference proceedings. The  
132 publications report on measurements of SOC concentration, SOC stock, and CO<sub>2</sub> and N<sub>2</sub>O  
133 emissions from pairwise comparisons of crop residue incorporation and crop residue removal  
134 management practices. The minimum requirements for data being included were that the

135 studies had i) replicates and ii) paired treatments that compared crop residue incorporation and  
136 removal. Further, we only included experiments in which crop residue incorporation and  
137 removal were investigated under the same climatic and soil conditions, as well as with similar  
138 fertilization levels. For CO<sub>2</sub> and N<sub>2</sub>O emissions, data from long-term experiments were scarce.  
139 For these variables, shorter experiment durations and laboratory experiments were included in  
140 the database. For this analysis, mostly publications reporting data in tables, which could be  
141 directly transferred into the database, were used. Data given in figures were extracted using the  
142 program WebPlotDigitizer (Rohatgi, 2013).

## 143 *2.2 Data preparation*

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

$$148 \text{BD} = (2.684 - 140.934 * 0.008) * \text{EXP}(-0.008 * \text{SOC})$$

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

152 SOC stock (Mg C ha<sup>-1</sup>) in the corresponding soil layer was calculated as:

$$153 \text{SOC stock} = \text{SOC} * \text{D} * \text{BD} * 10$$

154 where SOC is the concentration of soil organic carbon (g kg<sup>-1</sup>), D is the thickness of the soil layer  
155 (m), and BD is the soil bulk density (Mg m<sup>-3</sup>).

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

$$157 \text{RR} = \text{property}_I / \text{property}_R$$



158 where property<sub>I</sub> is the SOC concentration, SOC stock, CO<sub>2</sub> emission, or N<sub>2</sub>O emission in crop  
159 residue incorporation management practice, and property<sub>R</sub> is the SOC concentration, SOC stock,  
160 CO<sub>2</sub> emission, or N<sub>2</sub>O emission in crop residue removal management practice. RR >1 was  
161 assumed to be an improvement in SOC concentrations and stocks, whereas RR >1 for CO<sub>2</sub> and  
162 N<sub>2</sub>O emissions was assumed to be an undesirable increase in GHG emissions.

### 163 *2.3 Data aggregation*

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

### 171 *2.4 Data analysis*

172 The statistical analyses were performed using the IBM SPSS Statistics 20 software package for  
173 Mac. The normality of data was checked with Shapiro-Wilk's test. All data on SOC concentration,  
174 SOC stock and GHG emissions (CO<sub>2</sub> and N<sub>2</sub>O) were not normally distributed, thus log-  
175 transformed before the statistical analyses to obtain homogeneity of variances. A stepwise linear  
176 multiple regression was used to identify the significant continuous variables (temperature,  
177 precipitation, clay content, duration of the experiment were tested) on RR of SOC concentration,  
178 SOC stock, and GHG emissions (Table 3). To strengthen our analyses, the effect of the variables  
179 ENZ, clay content, and experiment duration (as aggregated into specific levels in Table 2) were  
180 investigated with ANOVA with Tukey's significance test ( $p < 0.05$ ) as a Post Hoc test. Correlations  
181 between variables were presented in Pearson correlation coefficients.

## 182 **3. Results**

183 Crop residue incorporation increased the SOC concentration and SOC on average by 7% (Figure  
184 1), whereas CO<sub>2</sub> emissions were increased almost six fold and N<sub>2</sub>O emissions more than twelve  
185 fold on average (n = 84 and 97, respectively). Multiple regressions revealed that experiment  
186 duration had highest effect on SOC concentration, explaining 14% of the variation (Table 3). For  
187 SOC stock, both clay content and experiment duration affected the response ratio and explained  
188 22% of the variation (Table 3). 98% of the variation in RR of CO<sub>2</sub> emissions was explained by  
189 clay content alone, whereas approximately 75% of the variation in RR of N<sub>2</sub>O emissions was  
190 explained by clay content and temperature (Table 3).

### 191 *3.1 Effect of environmental zone*

192 The effect of the aggregated ENZ on the response ratio of SOC concentration was not significant  
193 (Figure 2A). In contrast, the response ratio of the SOC stock was 4% lower in the Mediterranean  
194 versus the Continental Zone (Figure 2B). For GHG emissions, data were retrieved only for  
195 Atlantic and Mediterranean ENZs (Table 4). The RR for CO<sub>2</sub> for the Atlantic Zone was  
196 significantly higher than for the Mediterranean. For N<sub>2</sub>O emissions, RR was higher for the  
197 Atlantic Zone compared to Mediterranean, although not significantly due to the high variability  
198 normally associated with this measurement.

### 199 *3.2 Effect of clay content*

200 Among different clay contents, a content >35 % was found to be associated with significantly  
201 higher response ratios for SOC concentration compared to contents between 18 and 35 %  
202 (Figure 2C). The same was observed for SOC stocks (Figure 2D). Data for GHG emissions were  
203 retrieved only for the clay contents <18% and 18-35 % (Table 4). The RR for CO<sub>2</sub> for <18 % clay  
204 content was seven fold higher compared to 18-35 % clay content. For N<sub>2</sub>O, the effect of clay was  
205 similar as for CO<sub>2</sub>, being twice as high in soils with clay contents <18 % compared to 18-35 %.  
206 This difference, however, was not significant.

### 207 *3.3 Effect of experiment duration*

208 As the duration of the experiment rose, RR for SOC concentration increased (Figure 2E). The RR  
209 was statistically higher for experiments lasting >20 years compared to the other duration  
210 groups. Also, the RR for SOC stock was dependent on experiment duration (Figure 2F), being  
211 significantly lower in experiments <5 years compared to the duration groups 11-20 and >20  
212 years. For CO<sub>2</sub> (Table 4), no distinction between duration groups could be detected because all  
213 the RRs were in the <5 years group. For N<sub>2</sub>O, RR was significantly higher in experiments lasting  
214 <5 years compared to the 11-20 years duration. Note, however, that there was only one  
215 experiment in the 11-20 years duration group.

#### 216 *3.4 Effect of experiment and crop residue type on RR for GHG emissions*

217 We observed higher response ratios for CO<sub>2</sub> and N<sub>2</sub>O emissions in laboratory experiments  
218 compared to field experiments (Table 4), except for N<sub>2</sub>O emissions when cereal crop residues  
219 were incorporated. The RR was higher in vegetative material crop residue incorporation  
220 experiments compared to cereal crop residue incorporation experiments (Table 4). In field  
221 experiments for N<sub>2</sub>O emissions, however, the effect was opposite. This was a result of lower RR  
222 in vegetative material crop residue incorporation experiments compared to cereal crop residues  
223 in the Mediterranean environmental zone with 18-35 % clay content and less than five years  
224 experiment duration (Table 4).

#### 225 *3.5 Correlation between SOC concentration and crop yields*

226 The mean RR for yield was  $1.06 \pm 0.15$  (n=71). This means that crop residue incorporation  
227 resulted in an average 6 % yield increase compared to crop residue removal. We expected to  
228 observe an increase in SOC together with an increase in yield due to a positive feedback between  
229 crop residue incorporation, nutrient availability, crop nutrient uptake rate, and finally crop  
230 growth rate. From another perspective, higher crop yield means higher crop residue production,  
231 followed by higher SOC when these crop residues are incorporated. Unexpectedly, however, no  
232 significant correlation ( $r=0.02$ ,  $p>0.05$ ) was found between the RR of SOC concentration and the  
233 RR of yield. Differences between the studied sites (Figure 3A), ENZs (Figure 3B), and experiment

234 durations were found (Figure 3D). No differences were detected between different clay content  
235 groups (Figure 3C). No effect of crop type was recorded, but yield data were available only for  
236 the crops wheat, barley and maize. The sites Kesthely, Grossbeeren 2, and Ultuna had the highest  
237 RRs in both SOC concentration and yield, whereas Almacelles 1 and 2 were among the sites with  
238 lowest RRs. As the experiment duration increased, the RRs increased with the exception of  
239 Foggia 1 and Foggia 2, where RR for yields was below one even when the experiment lasted  
240 more than twenty years.

#### 241 **4. Discussion**

242 The results of this analysis demonstrate an increase in RR of SOC concentration and stock  
243 following crop residue incorporation (Figure 2) representing an additional annual C input. The  
244 same has been demonstrated in previous meta-analyses for organic inputs (Lemke et al., 2010;  
245 Powlson et al., 2012), e.g. in organic farming (Gattinger et al., 2012; Aguilera et al., 2013).  
246 Incorporation of crop residues is one of the few methods applied by farmers to maintain SOC  
247 and to sustain soil functions (Powlson et al., 2008). This makes it a very important management  
248 tool. Even a small increase in SOC can improve soil physicochemical and biological properties  
249 and ecosystem services such as nutrient cycling and possible increases in yields (Loveland and  
250 Webb, 2003; Bhogal et al., 2009; Blanco-Canqui, 2013).

251 The overall data for CO<sub>2</sub> and N<sub>2</sub>O emissions were collected from both field and laboratory  
252 experiments as well as from experiments that incorporated cereals and vegetative materials.  
253 Thus, the standard deviation was high for these indicators, possibly due to spatial heterogeneity  
254 driven by variability in soil characteristics. With crop residue incorporation, CO<sub>2</sub> emissions will  
255 increase compared to crop residue removal due to more easily available C that enhances  
256 microbial activity (Meijide et al., 2010). In contrast, if crop residues are removed, they will be  
257 decomposed elsewhere, used as bedding and incorporated into farmyard manure or burned,  
258 releasing approximately the same amount of CO<sub>2</sub> (Blanco-Canqui, 2013). Thus, crop residue  
259 incorporation is not primarily a way to decrease CO<sub>2</sub> emissions and may not be beneficial for all

260 soil ecosystem services such as carbon sequestration. In order to close the knowledge gap and to  
261 give better-informed recommendations to farmers, further field-scale research focusing on in  
262 situ carbon balance is required.

263 In the case of N<sub>2</sub>O, emissions from crop residue incorporation are up to twelve times higher  
264 compared to crop residue removal. Emissions of N<sub>2</sub>O occur both during the nitrification process  
265 and as a result of anaerobic denitrification. The latter process requires the presence of microbes  
266 capable of using nitrates. The increase of the RR for N<sub>2</sub>O following crop residue incorporation in  
267 a study by Baggs et al. (2003) was explained by mineral N fertilization and an increased  
268 denitrification capacity stimulated by the added substrate. In our analysis, no distinct  
269 relationships were found with mineral N fertilisation ( $r=0.08$ ,  $p>0.05$ ), most likely due to the  
270 limited number of data. The soil respiration process may create anaerobic microsites in the soil  
271 and thereby increase N<sub>2</sub>O emissions through denitrification (Garcia-Ruiz and Baggs, 2007;  
272 Abalos et al., 2013). Nonetheless, the N<sub>2</sub>O emissions caused by the crop residues should be put in  
273 relation to the fact that not all removed crop residues are decomposed or burned with no N<sub>2</sub>O  
274 emissions.

#### 275 *4.1 Effect of environmental zone*

276 The aggregated ENZ proved not to be a determining factor when RRs for SOC concentration, SOC  
277 stock, CO<sub>2</sub> and N<sub>2</sub>O emissions were studied (Figure 2, Table 4). This is in contrast with concepts  
278 in which climate is directly and indirectly linked with carbon concentrations in soils (e.g. Ingram  
279 & Fernandes, 2001). One explanation may be that the aggregated ENZs in our study were too  
280 broad categories to capture the differences between different climates. ENZ are assigned based  
281 on several factors beyond climate, such as geomorphology, vegetation and fauna (Metzger et al.,  
282 2005). Given the large heterogeneity in these environmental factors across the experimental  
283 sites in this study, probably more data would have been required to detect significant  
284 differences between ENZs. In previous studies, temperature has been found to be one of the

285 driving factors for both N<sub>2</sub>O (Mutegi et al., 2010) and CO<sub>2</sub> emissions (Meijide et al., 2010). This  
286 was also supported by our multiple regressions, in the case of N<sub>2</sub>O (Table 3).

#### 287 *4.2 Effect of clay content*

288 Our results indicated higher RR for SOC concentration and stock with higher clay content (Figure  
289 2C, D), probably because the clay fraction physically protects organic matter molecules from  
290 mineralization (Lal, 1997). SOM may be physically protected in the clay fraction of fine-textured  
291 soils by chemical bonds due to high surface activity (Six et al., 2000), thereby being inaccessible  
292 for microbial degradation (von Lützow et al., 2006). Nonetheless, the low clay content (<18 %)  
293 soils also showed a positive SOC response to management changes (Cvetkov and Tajnsek, 2009).  
294 This may be explained by SOC being accumulated as POM in the sand fraction of these soils, and  
295 not additionally in the clay fraction, as has been shown in tropical soils (Feller and Beare, 1997;  
296 Chivence et al., 2007). Furthermore, the initial SOC concentration of the soil may play a role in  
297 how much C is retained in the fine fraction (Poirier et al., 2013). The authors showed that low-  
298 SOC-concentration soils have a greater capacity to accumulate C in the fine fraction when high  
299 amounts of crop residues are added to the soil.

300 For GHG emissions the number of experiments and RRs was too small to allow a representative  
301 analysis of differences between clay content groups. Velthof et al. (2002) compared sandy and  
302 clay soils under laboratory conditions and found the N<sub>2</sub>O emissions to be much lower in the  
303 latter than in the former. This is supported by our analysis of field data on cereal crop residue  
304 incorporation (Table 4), but more measurements would be necessary before generalisations  
305 could be made. Indications of lower RR of N<sub>2</sub>O emission in lower-clay-content soils are in  
306 accordance with a recent meta-analysis that confirmed the influence of texture on N<sub>2</sub>O emissions  
307 (Chen et al., 2013). Soil texture may influence the response to crop residue incorporation  
308 through O<sub>2</sub> availability in soil microsites and its influence on denitrification (Chen et al., 2013).

#### 309 *4.3 Effect of experiment duration*

310 The observed higher response ratios for SOC concentration and stock for longer experiment  
311 durations (Figure 2) agree with previous studies (Körschens et al., 1998). The low clay-content  
312 (<18 %) soils showed a positive SOC response to management changes after ten years of  
313 management difference (Cvetkov and Tajnsek, 2009), but it may be that SOC saturation in soils  
314 with low clay content is reached faster than in high content (>35 %). As experiment duration  
315 increases, more interactions between clay minerals and SOC may take place (von Lützwow et al.,  
316 2006); this is accompanied by a more marked accumulation of resistant crop residue C that is  
317 not mineralised (De Neve and Hofman, 2000), especially in soils without mechanical tillage (Six  
318 et al., 2000). Hence, the increase in SOC concentration has its limits and the accumulation rate  
319 becomes smaller when the soil system is close to a new equilibrium (Powlson et al., 2008).

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

#### 326 *4.4 Effect of experiment and crop residue type on RR for GHG emissions*

327 The higher response ratios of N<sub>2</sub>O emissions in vegetative material laboratory experiments  
328 compared to field experiments (Table 4) agree with a meta-analysis that studied N<sub>2</sub>O emissions  
329 following crop residue incorporation (Chen et al., 2013). Those authors explained the difference  
330 by the smaller size and subsequent increase of surface area of the crop residues in the  
331 laboratory experiments compared to field-scale applications. This applies to laboratory  
332 experiments in our analysis (Velthof et al., 2002; Garcia-Ruiz & Baggs, 2007; Cayuela et al.,  
333 2013), compared to the field experiments (Baggs et al., 2003; Mutegi et al., 2010; Abalos et al.,  
334 2013; Sanz-Cobena et al., 2014). Moreover, under laboratory conditions moisture and

335 temperature are stable and optimised for microbial activity, thus promoting higher emissions  
336 compared to field experiments (Chen et al., 2013).

337 Previous studies show that N<sub>2</sub>O emissions decrease at a higher C/N ratio of the residues  
338 (Alexander, 1977; Shan and Yan, 2013). This is in line with the observed higher RR of GHG  
339 emissions (Table 4) in vegetative material crop residue incorporation experiments compared to  
340 cereal crop residue incorporation experiments in our study. This may be explained by  
341 immobilisation of N with increasing C/N ratio of the crop residues (Abalos et al., 2013). The  
342 oxidation rate is higher immediately after the incorporation of vegetative material (versus cereal  
343 residues) due to quick decomposition, thus possibly promoting higher denitrification rates  
344 (Nicolardot et al., 2001; Rizhiya et al., 2011). Higher GHG emissions from low-C/N-ratio crop  
345 residue incorporation were observed in individual studies under field conditions in our analysis  
346 (e.g. Baggs et al., 2000; 2003). This can be explained by higher availability of N first for  
347 nitrification and then for denitrification when the C/N ratio of incorporated crop residue is low  
348 (Baggs et al., 2003). Garcia-Ruiz and Baggs (2007), however, stated that more knowledge on the  
349 interactions between organic and inorganic N sources and compounds released from the crop  
350 residues is required before drawing conclusions on how to reduce GHG emissions following crop  
351 residue incorporation.

352 One additional explanation for the RR of GHG emissions may be the cultivation technique, which  
353 affects the nutrient supply to microorganisms and the aeration (Baggs et al., 2003; Mutegi et al.,  
354 2010). However, soil tillage was not in the scope of this study. Another potential factor is N  
355 fertilisation, which increased GHG emissions in several studies (e.g. Garcia-Ruiz and Baggs,  
356 2007; Meijide et al., 2010; Sanz-Cobena et al., 2014). Nevertheless, our analysis did not reveal  
357 any significant correlations between N<sub>2</sub>O emissions and mineral N fertilisation. This may be due  
358 to limited data accessibility and differences in the set-up of the experiments we investigated. The  
359 differences observed between ENZs, clay content groups and experiment durations within  
360 experiment types and crop residue types most likely reflected differences between experiments



361 and not between the categories. More data from long-term field experiments are required to  
362 enable a study of such relationships.

#### 363 *4.5 Correlations between crop yields and SOC concentrations*

364 The slight positive influence of crop residue incorporation on crop yield (Figure 3A) contradicts  
365 previous studies reporting yield decreases (Swan et al. 1994; Nicholson et al., 1997), but agrees  
366 with Wilhelm et al. (2004). The positive influence of crop residue incorporation may be  
367 explained by the increase in SOC and the experiment duration (Figure 3A, D). Crop residues act  
368 as a continuous source of soil nutrients and soil organic matter (Liu et al., 2014), which  
369 improves soil functioning (Bhogal et al., 2009) and thereby yields. Thus, a positive feedback,  
370 initiated by incorporation of crop residues, occurs. In the case of the Foggia experiment (Figure  
371 3A), the incorporation of crop residues lowered yield because of the poor mineralisation and  
372 strong N immobilisation due to arid climate and the low soil N status (Maiorana, 1998). Mineral  
373 N fertilization did not increase yields at Almacelles even though SOC concentrations were  
374 sufficient, possibly due to the short duration of the experiment and the arid climate (Biau et al.,  
375 2013).

#### 376 *4.6 Possible improvements of the data set for future analyses*

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

## 385 **5. Conclusions**

386 This analysis indicates that the impacts of crop residue incorporation on SOC concentration and  
387 stock are positive, but the CO<sub>2</sub> and N<sub>2</sub>O emissions are increased. Even a small decrease in SOC  
388 may have detrimental effects on other soil properties such as aggregate stability. Thus,  
389 maintaining or even increasing SOC levels is crucial for agricultural soils. We show that long-  
390 term crop residue incorporation may increase crop yields. A win-win scenario between yield  
391 and SOC is crop residue incorporation over the longer term (>20 years) in a continental climate.  
392 The worst-case scenario would occur with short-term crop residue incorporation, especially  
393 with vegetative material, in a Mediterranean setting. Data availability from field experiments on  
394 GHG emissions is still scarce, and the data do not allow for selection of win-win and worst-case  
395 scenarios for these parameters. Thus, more long-term field studies are needed to better assess  
396 the CO<sub>2</sub> and N<sub>2</sub>O emissions following crop residue incorporation, specifically from the same  
397 studies in which SOC is measured. We conclude that crop residue incorporation is an important  
398 management practice to maintain SOC concentrations and stocks and to sustain soil functioning,  
399 but that its influence on GHG emissions should be considered. GHG emissions should be  
400 measured in on-going long-term field experiments to more accurately calculate trade-offs such  
401 as in situ SOC and GHG balances following crop residue management in agricultural systems.

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410 **References**

- 411 Abalos, D., Sanz-Cobena, A., Garcia-Torres, L., van Groenigen, J.W. & Vallejo, A. 2013. Role of  
412 maize stover incorporation on nitrogen oxide emissions in a non-irrigated Mediterranean  
413 barley field. *Plant and Soil*, **364**, 357-371.
- 414 Aguilera, E., Lassaletta, L., Gattinger, A. & Gimeno, B.S. 2013. Managing soil carbon for climate  
415 change mitigation and adaptation in Mediterranean cropping systems: A meta-analysis.  
416 *Agriculture, Ecosystems and Environment*, **168**, 25-36.
- 417 Albert, E. & Grunert, M. 2013. Wirkung einer langjährig differenzierten mineralisch-organischen  
418 Düngung auf Ertrag, Humusgehalt, N-Bilanz und Nährstoffgehalte des Bodens. *Archives of*  
419 *Agronomy and Soil Science*, **59**, 1073-1098.
- 420 Alexander, M. 1977. Mineralization and immobilization of nitrogen, In: Introduction to soil  
421 microbiology, 2<sup>nd</sup> edition (ed Alexander, M.). Wiley, New York, USA, pp. 136-247.
- 422 Baggs, E.M., Stevenson, M., Pihlatie, M., Regar, A., Cook, H. & Cadisch, G. 2003. Nitrous oxide  
423 emissions following application of residues and fertiliser under zero and conventional tillage.  
424 *Plant and Soil*, **254**, 361-370.
- 425 Baggs, E.M., Rees, R.M., Smith, K.A. & Vinten, A.J.A. 2000. Nitrous oxide emission from soils after  
426 incorporating crop residues. *Soil Use and Management*, **16**, 82-87.
- 427 Ball, B.C., Bickerton, D.C. & Robertson, E.A.G. 1990. Straw incorporation and tillage for winter  
428 barley: Soil structural effects. *Soil and Tillage Research*, **15**, 309-327.
- 429 Bertora, C., Zavattaro, L., Sacco, D., Monaco, S. & Grignani, C. 2009. Soil organic matter dynamics  
430 and losses in manured maize-based forage systems. *European Journal of Agronomy*, **30**, 177-  
431 186.
- 432 Bhogal, A., Nicholson, F.A., & Chambers, B.J. 2009. Organic carbon additions: effects on soil bio-  
433 physical and physico-chemical properties. *European Journal of Soil Science*, **60**, 276-286.

434 Bianchi, A.A., Guiducci, M. & Bonciarelli, U. 1994. Effect of crop rotation and nitrogen fertilization  
435 on PAR absorption and radiation use efficiency of winter bread wheat. *Proceedings to the*  
436 *Third congress of the European Society for Agronomy*, pp. 70-71.

437 Biau, A., Santiveri, F. & Lloveras, J. 2013. Stover Management and Nitrogen Fertilization Effects  
438 on Corn Production. *Agronomy Journal*, **105**, 1264-1270.

439 Blanco-Canqui, H. 2013. Crop Residue Removal for Bioenergy Reduces Soil Carbon Pools: How  
440 Can We Offset Carbon Losses? *Bioenergy Research*, **6**, 358-371.

441 Börjesson, G., Menichetti, L., Kirchmann, H. & Kätterer, T. 2012. Soil microbial community  
442 structure affected by 53 years of nitrogen fertilisation and different organic amendments.  
443 *Biology and Fertility of Soils*, **48**, 245-257.

444 Børresen, T., 1999. The effect of straw management and reduced tillage on soil properties and  
445 crop yields of spring-sown cereals on two loam soils in Norway. *Soil & Tillage Research*, **51**,  
446 91-102.

447 Cayuela, M.L., Kuikman, P., Bakkers, R. & van Groenigen, J.W. 2013. Tracking C and N dynamics  
448 and stabilization in soil amended with wheat residue and its corresponding bioethanol by-  
449 product: a <sup>13</sup>C/<sup>15</sup>N study. *Global Change Biology Bioenergy*, DOI: 10.1111/gcbb.12102.

450 Chen, H., Li, X., Hu, F. & Shi, W. 2013. Soil nitrous oxide emissions following crop residue  
451 addition: a meta-analysis. *Global Change Biology*, **19**, 2956-2964.

452 Chivenge, P.P., Murwira, H.K., Giller, K.E., Mapfumo, P. & Six, J. 2007. Long-term impact of  
453 reduced tillage and residue management on soil carbon stabilization: Implications for  
454 conservation agriculture on contrasting soils. *Soil & Tillage Research*, **94**, 328-337.

455 Cvetkov, M., Santavec, I., Kocjan Acko, D. & Tajnsek, A. 2010. Soil organic matter content  
456 according to different management system within long-term experiment. *Acta agriculturae*  
457 *Slovenica*, **95**, 79-88.

458 Cvetkov, M. & Tajnsek, A. 2009. Soil organic matter changes according to the application of  
459 organic and mineral fertilizers within long-term experiments. *Acta agriculturae Slovenica*, **93**,  
460 311-320.

461 De Neve, S. & Hofman, G. 2000. Influence of soil compaction on carbon and nitrogen  
462 mineralization of soil organic matter and crop residues. *Biology and Fertility of Soils*, **30**, 544-  
463 549.

464 European Commission. 2006. Thematic Strategy for Soil Protection. Commission of the European  
465 Communities, Brussels, Belgium, COM(2006) 231. Available at: [eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2006:0231:FIN:EN:PDF](http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2006:0231:FIN:EN:PDF);  
466 accessed  
467 12/16/2013.

468 Feller, C. & Beare, M.H. 1997. Physical control of soil organic matter dynamics in the tropics.  
469 *Geoderma*, **79**, 69-116.

470 Garcia-Ruiz, R. & Baggs, E.M. 2007. N<sub>2</sub>O emission from soil following combined application of  
471 fertilizer-N and ground weed residues. *Plant and Soil*, **299**, 263-274.

472 Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mäder, P., Stolze, M.,  
473 Smith, P., El-Hage Scialabba, N. & Niggli, U. 2012. Enhanced top soil carbon stocks under  
474 organic farming. *Proceedings of the National Academy of Sciences*, **109**, 18226-18231.

475 Grignani, C., Zavattaro, L., Sacco, D. & Monaco, S. 2007. Production, nitrogen and carbon balance  
476 of maize-based forage systems. *European Journal of Agronomy*, **26**, 442-453.

477 Hege, U. & Offenberger, K. 2006. Effect of differentiated mineral fertilization and organic  
478 manuring on yield, product quality and N balances in the international permanent organic  
479 nitrogen experiment (IOSDV) Puch. *Archives of Agronomy and Soil Science*, **52**, 535-550.

480 Ingram, J.S.I. & Fernandes, E.C.M. 2001. Managing carbon sequestration in soils: concepts and  
481 terminology. *Agriculture, Ecosystems & Environment*, **87**, 111-117.

482 Janowiak, J. 1995. Influence of manure fertilization with straw addition and different nitrogen  
483 doses on properties of organic matter. *Zeszyty Problemowe postepów nauk rolniczych*, **421a**,  
484 145-150.

485 Jongman, R.H.G., Bunce, R.G.H., Metzger, M.J., Múcher, C.A., Howard, D.C. & Mateus, V.L. 2006.  
486 Objectives and applications of a statistical environmental stratification of Europe. *Landscape*  
487 *Ecology*, **21**, 409–419.

488 Körschens, M. 2006. The importance of long-term field experiments for soil science and  
489 environmental research – a review. *Plant, Soil and Environment*, **52**, 1-8.

490 Körschens, M., Weigel, A. & Schulz, E. 1998. Turnover of Soil Organic Matter (SOM) and Long-  
491 Term Balances – Tools for Evaluating Sustainable Productivity of Soils. *Zeitschrift für*  
492 *Pflanzenernährung und Bodenkunde*, **161**, 409-424.

493 Lajeunesse, M.J. 2011. On the meta-analysis of response ratios for studies with correlated and  
494 multi-group designs. *Ecology*, **92**, 2049-2055.

495 Lal, R. 2013. Intensive Agriculture and the Soil Carbon Pool. *Journal of Crop Improvement*, **27**,  
496 735-751.

497 Lal, R. 1997. Residue management, conservation tillage and soil restoration for mitigating  
498 greenhouse effect by CO<sub>2</sub>-enrichment. *Soil & Tillage Research*, **43**, 81-107.

499 Leinweber, P. & Reuter, G. 1992. The influence of different fertilization practices on  
500 concentrations of organic carbon and total nitrogen in particle-size fractions during 34 years  
501 of a soil formation experiment in loamy marl. *Biology and Fertility of Soils*, **13**, 119-124.

502 Lemke, R.L., Van den Bygaart, A.J., Campbell, C.A., Lafond, G.P. & Grant, B. 2010. Crop residue  
503 removal and fertilizer N: Effects on soil organic carbon in a long-term crop rotation  
504 experiment on a Udic Boroll. *Agriculture, Ecosystems and Environment*, **135**, 42-51.

505 Liu, C., Lu, M., Cui, J., Li, B. & Fang, C. 2014. Effects of straw carbon input on carbon dynamics  
506 in agricultural soils: a meta-analysis. *Global Change Biology*, doi: 10.1111/gcb.12517.

507 Loveland, P. & Webb, J. 2003. Is there a critical level of organic matter in the agricultural soils of  
508 temperate regions: a review. *Soil & Tillage Research*, **70**, 1-18.

509 Lubet, E., Plénet, D. & Juste, C. 1993. Effet à long terme de la monoculture sur le rendement en  
510 grain du maïs (*Zea mays* L) en conditions non irriguées. *Agronomie*, **13**, 673-683.

511 Maiorana, M., Convertini, G. & Fornaro, F. 2004. Gestione del suolo nella omosuccessione di  
512 grano duro. *Informatore agrario*, **60**, 79-82.

513 Maiorana, M. 1998. Interramento dei residui colturali di frumento duro. *Informatore agrario*, **54**,  
514 41-45.

515 Marschner, P., Kandeler, E. & Marschner, B. 2003. Structure and function of the soil microbial  
516 community in a long-term fertilizer experiment. *Soil Biology & Biochemistry*, **35**, 453-461.

517 Meijide, A., Cárdenas, L.M., Sánchez-Martín, L. & Vallejo, A. 2010. Carbon dioxide and methane  
518 fluxes from a barley field amended with organic fertilizers under Mediterranean climatic  
519 conditions. *Plant and Soil*, **328**, 353-367.

520 Metzger, M.J., Bunce, R.G.H., Jongman, R.H.G., Múcher, C.A. & Watkins, J.W. 2005. A climatic  
521 stratification of the environment of Europe. *Global Ecology and Biogeography*, **14**, 549-563.

522 MLUV (Ministerium für Ländliche Entwicklung, Umwelt und Verbraucherschutz des Landes  
523 Brandenburg). 2009. Dauerfeldversuche in Brandenburg und Berlin - Beiträge für eine  
524 nachhaltige Landwirtschaftliche Bodennutzung. Available at:  
525 <http://lelf.brandenburg.de/sixcms/media.php/4055/Dauerfeldversuche%20f%C3%BCr%20nachhaltige%20Landwirtschaftliche%20Bodennutzung.pdf>; accessed at 11/6/2013.

527 Murphy, D.V., Stockdale, E.A., Poulton, P. R., Willison, T. W. & Goulding, K.W.T. 2007. Seasonal  
528 dynamics of carbon and nitrogen pools and fluxes under continuous arable and ley-arable  
529 rotations in a temperate environment. *European Journal of Soil Science*, **58**, 1410-1424.

530 Mutegi, J.K., Munkholm, L.J., Petersen, B.M., Hansen, E.M. & Petersen, S.O. 2010. Nitrous oxide  
531 emissions and controls as influenced by tillage and crop residue management strategy. *Soil*  
532 *Biology & Biochemistry*, **42**, 1701-1711.

533 Nedved, V., Balík, J., Cerný, J., Kulhánek, M. & Balíková, M. 2008. The changes of soil nitrogen and  
534 carbon contents in a long-term field experiment under different systems of nitrogen  
535 fertilization. *Plant, Soil and Environment*, **54**, 463-470.

536 Nicholson, F.A., Chambers, B.J., Mills, A.R. & Strachan, P.J. 1997. Effects of repeated straw  
537 incorporation on crop fertilizer nitrogen requirements, soil mineral nitrogen and nitrate  
538 leaching losses. *Soil Use and Management*, **13**, 136-142.

539 Nicolardot, B., Recous, S. & Mary, B. 2001. Simulation of C and N mineralisation during crop  
540 residue decomposition: A simple dynamic model based on the C:N ratio of the residues. *Plant*  
541 *and Soil*, **228**, 83-103.

542 Perucci, P., Bonciarelli, U., Santilocchi, R. & Bianchi, A.A. 1997. Effect of rotation, nitrogen  
543 fertilization and management of crop residues on some chemical, microbiological and  
544 biochemical properties of soil. *Biology and Fertility of Soils*, **24**, 311-316.

545 Petersen, S.O., Mutegi, J.K., Hansen, E.M. & Munkholm, L.J. 2011. Tillage effects on N<sub>2</sub>O emissions  
546 as influenced by a winter cover crop. *Soil Biology & Biochemistry*, **43**, 1509-1517.

547 Plénet, D., Lubet, E. & Juste, C. 1993. Évolution á long terme du statut carboné du sol en  
548 monoculture non irriguée du maïs (*Zea mays* L). *Agronomie*, **13**, 685-698.

549 Poirier, V., Angers, D.A., Rochette, P. & Whalen, J.K. 2013. Initial soil organic carbon  
550 concentration influences the short-term retention of crop-residue carbon in the fine fraction  
551 of a heavy clay soil. *Biology and Fertility of Soils*, **49**, 527-535.

552 Powlson, D.S., Bhogal, A., Chambers, B.J., Coleman, K., Macdonald, A.J., Goulding, K.W.T. &  
553 Whitmore, A.P. 2012. The potential to increase soil carbon stocks through reduced tillage or  
554 organic material additions in England and Wales: A case study. *Agriculture, Ecosystems and*  
555 *Environment*, **146**, 23-33.



- 556 Powlson, D.S., Glendining, M.J., Coleman, K. & Whitmore, A.P. 2011. Implications for Soil  
557 Properties of Removing Cereal Straw: Results from Long-Term Studies. *Agronomy Journal*,  
558 **103**, 279-287.
- 559 Powlson, D.S., Riche, A.B., Coleman, K., Glendining, M.J. & Whitmore, A.P. 2008. Carbon  
560 sequestration in European soils through straw incorporation: Limitations and alternatives.  
561 *Waste Management*, **28**, 741-746.
- 562 Recous, S., Robin, D., Darwis, D. & Mary, B. 1995. Soil inorganic N availability: Effect on maize  
563 residue decomposition. *Soil Biology and Biochemistry*, **27**, 1529–1538.
- 564 Rizhiya, E.Y., Boitsova, L.V., Buchkina, N.P. & Panova, G.G. 2011. The influence of crop residues  
565 with different C:N ratios on the N<sub>2</sub>O emission from a loamy sand soddy-podzolic soil. *Eurasian*  
566 *Soil Science*, **44**, 1144-1151.
- 567 Rogasik, J., Schroetter, S., Schnug, E. & Kundler, P. 2001. Langzeiteffekte ackerbaulicher  
568 massnahmen auf die bodenfruchtbarkeit. *Archives of Agronomy and Soil Science*, **47**, 3-17.
- 569 Rohatgi, A. 2013. WebPlotDigitizer Version 2.6. Available at:  
570 <http://arohatgi.info/WebPlotDigitizer>; accessed at 12/11/2013.
- 571 Ruehlmann, J. & Körschens, M. 2009. Calculating the Effect of Soil Organic Matter Concentration  
572 on Soil Bulk Density. *Soil Science Society of America Journal*, **73**, 876-885.
- 573 Rühlmann, J., Körschens, M. & Graefe, J. 2006. A new approach to calculate the particle density of  
574 soils considering properties of the soil organic matter and the mineral matrix. *Geoderma*, **130**,  
575 272-283.
- 576 Rühlmann, J. 2006. The Box Plot Experiment in Grossbeeren after six rotations: Effect of  
577 fertilization on crop yield. *Archives of Agronomy and Soil Science*, **52**, 313-319.
- 578 Rühlmann, J. & Ruppel, S. 2005. Effects of organic amendments on soil carbon content and  
579 microbial biomass – results of the long-term box plot experiment in Grossbeeren. *Archives of*  
580 *Agronomy and Soil Science*, **51**, 163-170.

581 Sanz-Cobena, A., García-Marco, S., Quemada, M., Gabriel, J.L., Almendros, P. & Vallejo, A. 2014. Do  
582 cover crops enhance N<sub>2</sub>O, CO<sub>2</sub> or CH<sub>4</sub> emissions from soil in Mediterranean arable systems?  
583 *Science of the Total Environment*, **466-467**, 164-174.

584 Shan, J. & Yan, X. 2013. Effects of crop residue returning on nitrous oxide emissions in  
585 agricultural soils. *Atmospheric Environment*, **71**, 170-175.

586 Simon, T., Mikanova, O. & Cerhanova, D. 2013. Long-term effect of straw and farmyard manure  
587 on soil organic matter in field experiment in the Czech Republic. *Archives of Agronomy and*  
588 *Soil Science*, **59**, 1193-1205.

589 Smith, W.N., Grant, B.B., Campbell, C.A., McConkey, B.G., Desjardins, R.L., Kröbel, R., & Malhi, S.S.  
590 2012. Crop residue removal effects on soil carbon: Measured and inter-model comparisons.  
591 *Agriculture, Ecosystems and Environment*, **161**, 24-38.

592 Spiegel, H., Dersch, G. & Baumgarten, A. 2010a. Long term field experiments - a basis to evaluate  
593 parameters of soil fertility. In: New Challenges in field crop production 2010, Proceedings of  
594 Symposium (eds D. Kocjan Acko & B. Ceh), Slovensko agronomsko drustvo, Ljubljana,  
595 Slovenia, pp.76-82.

596 Spiegel, H., Dersch, G., Baumgarten, A. & Hösch, J. 2010b. The International Organic Nitrogen  
597 Long-term Fertilisation Experiment (IOSDV) at Vienna after 21 years. *Archives of Agronomy*  
598 *and Soil Science*, **56**, 405-420.

599 Swan, J.B., Higgs R.L., Bailey T.B., Wollenhaupt N.C., Paulson W.H. & Peterson A.E. 1994. Surface  
600 residue and in-row treatment on long-term no-tillage continuous corn. *Agronomy Journal*, **86**,  
601 711-718.

602 Tajnsek, A., Cergan, Z. & Ceh, B. 2013. Results of the long-term field experiment IOSDV Rakican at  
603 the beginning of the 21<sup>st</sup> century. *Archives of Agronomy and Soil Science*, **59**, 1109-1119.

604 Triberti, L., Nastri, A., Giordani, G., Comellini, F., Baldoni, G. & Toderi, G. 2008. Can mineral and  
605 organic fertilization help sequester carbon dioxide in cropland? *European Journal of*  
606 *Agronomy*, **29**, 13-20.

607 Kismányoky, T. & Toth, Z. 2010. Effect of mineral and organic fertilization on soil fertility as well  
608 as on the biomass production and N utilization of winter wheat (*Triticum aestivum* L.) in a  
609 long-term cereal crop rotation experiment (IOSDV). *Archives of Agronomy and Soil Science*,  
610 **56**, 473-479.

611 Lugato, E., Berti, A. & Giardini, L. 2006. Soil organic carbon (SOC) dynamics with and without  
612 residue incorporation in relation to different nitrogen fertilization rates. *Geoderma*, **135**, 315-  
613 321.

614 Uhlen, G. 1991. Long-Term Effects of Fertilizers, Manure, Straw and Crop-Rotation on Total-N  
615 and Total-C in Soil. *Acta Agriculturae Scandinavica*, **41**, 119-127.

616 Velthof, G.L., Kuikman, P.J. & Oenema, O. 2002. Nitrous oxide emission from soils amended with  
617 crop residues. *Nutrient Cycling in Agroecosystems*, **62**, 249-261.

618 von Lützow M., Kögel- Knabner I., Ekschmitt K , Matzner E., Guggenberger G., Marschner B. &  
619 Flessa H., 2006. Stabilization of organic matter in temperate soils: mechanisms and their  
620 relevance under different soil conditions - a review. *European Journal of Soil Science*, **57**, 426-  
621 445.

622 Wilhelm, W.W., Johnson, J.M.F., Hatfield, J.L., Voorhees, W.B. & Linden, D.R. 2004. Crop and soil  
623 productivity response to corn residue removal. *Agronomy Journal*, **96**, 1-17.

624 Zavattaro, L., Monaco, S., Sacco, D. & Grignani, C. 2012. Options to reduce N loss from Maize in  
625 intensive cropping systems in Northern Italy. *Agriculture, Ecosystems and Environment*, **147**,  
626 24-35.

627

628 **Figures**

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

631 **Figure 2** Response ratios (RRs) in A,C,E) SOC concentrations, and B,D,F) SOC stocks across A,B)  
632 environmental zones (ENZs), C,D) clay contents (%), and E,F) experiment durations (years). The  
633 left vertical line of the box represents the first quartile, median is shown as a thick line, and the  
634 right vertical line represents the third quartile. Horizontal bars show the minimum and  
635 maximum values. The (°) and (\*) denote outliers. The figure is based on the original data on  
636 response ratios, without any weighting procedure. The numbers of RR (and experiments) are  
637 presented for each category along the y-axis. Different letters indicate significant differences  
638 according to Tukey's as a Post Hoc test ( $p < 0.05$ ).

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

643 **Tables**

644 **Table 1** Description of sites included in the analysis.

645 **Table 2** Aggregated variables and specific levels of each variable.

646 **Table 3** Significant results of multiple regressions.

647 **Table 4** Mean response ratios of GHG emissions in crop residue incorporation management  
648 practice compared to crop residue removal management practice in different environmental  
649 zones (ENZ), clay contents (%), and experiment durations (years). The values have been  
650 calculated from average data from each experiment and were weighted based on the amount of  
651 response ratios calculated into the average.

**Table 1** Summary description of sites included in the analysis.

Experiment Nr	Experiment	Country	Location	Environmental zone <sup>a</sup>	Start year	Soil texture	References
<i>Field studies</i>							
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
<i>Laboratory studies</i>							
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

<sup>a</sup>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 <sup>a</sup>	Nemoral (NEM)	Atlantic (ATN, ATC, LUS)	Continental (CON, PAN, ALS)	Mediterranean (MDM, MDN, MDS)
Clay %	<18 %	18-35 %	>35%	
Experiment duration <sup>b</sup>	<5 years	5-10 years	11-20 years	>20 years

<sup>a</sup>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.

<sup>b</sup> Experiment duration: years between the beginning of the experiment and the measurement.



**Table 3** Significant results of multiple regressions.

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<i>LOG RR of SOC concentration</i>					
	R <sup>2</sup>	F	P	n	
Model	0.140	34.385	<0.0001	213	
Variables	Coefficient	SE <sup>a</sup>	95% CI <sup>b</sup>	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

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<i>LOG RR of SOC stock</i>					
	R <sup>2</sup>	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

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<i>LOG RR of CO<sub>2</sub> emissions</i>					
	R <sup>2</sup>	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

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*LOG RR of N<sub>2</sub>O emissions*

Model	R <sup>2</sup>	F	P	n	
	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

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<sup>a</sup>SE, standard error

<sup>b</sup>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 <sub>2</sub>				CO <sub>2</sub>			
		Mean	SD <sup>a</sup>	n exp <sup>b</sup>	n RR <sup>c</sup>	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
<i>ENZ</i>									
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
<i>Clay %</i>									
<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
<i>Duration</i>									
< 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 <sub>2</sub> O				N <sub>2</sub> O			
		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
<i>ENZ</i>									
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
<i>Clay %</i>									
<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
<i>Duration</i>									
<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

<sup>a</sup>SD, standard deviation.

<sup>b</sup>n exp, number of experiments.

<sup>c</sup>n RR, number of response ratios; RR, CO<sub>2</sub> or N<sub>2</sub>O emissions in crop residue incorporation treatment/CO<sub>2</sub> or N<sub>2</sub>O emissions in crop residue removal treatment.

N/A, not available.

Figure 1.

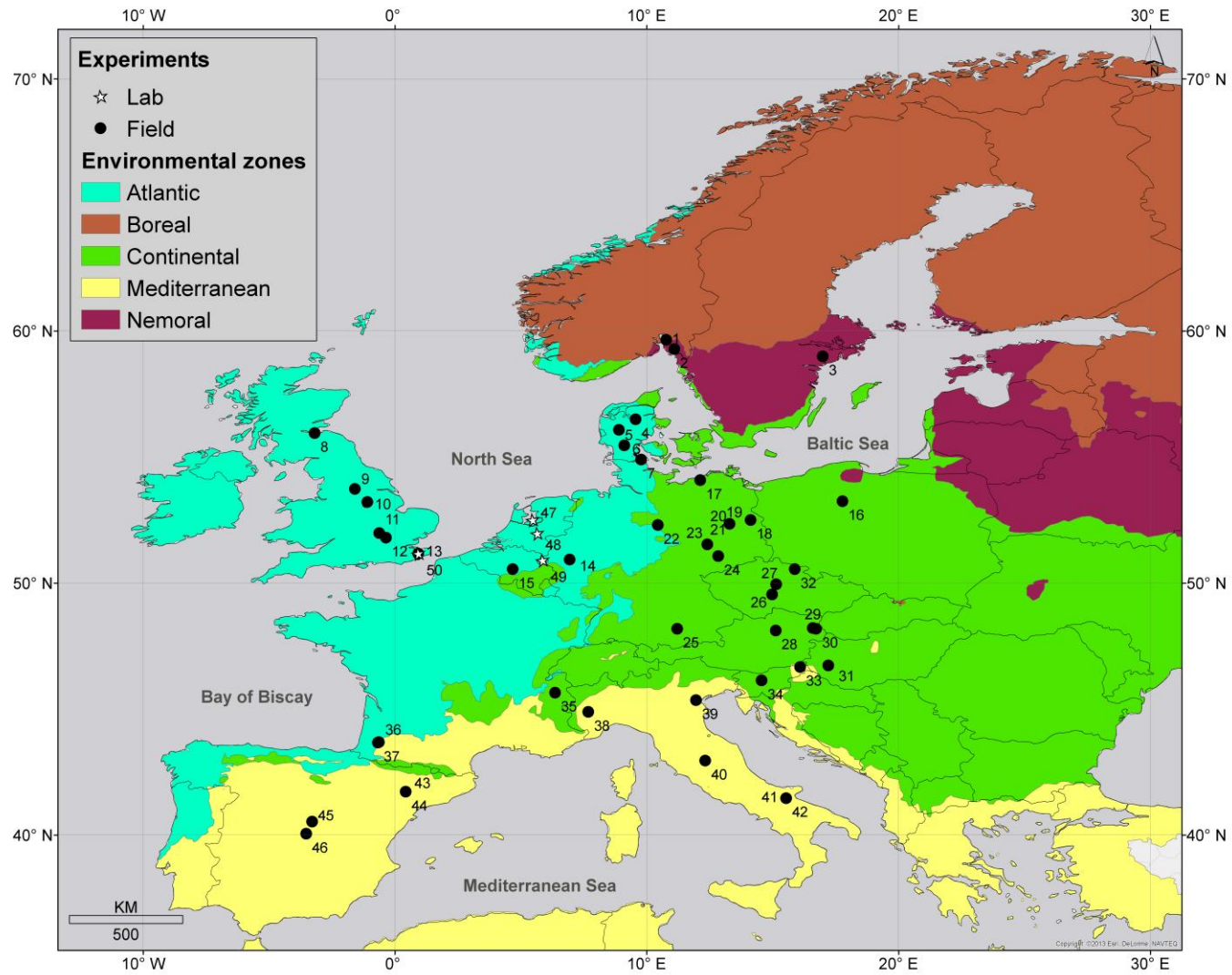


Figure 2.

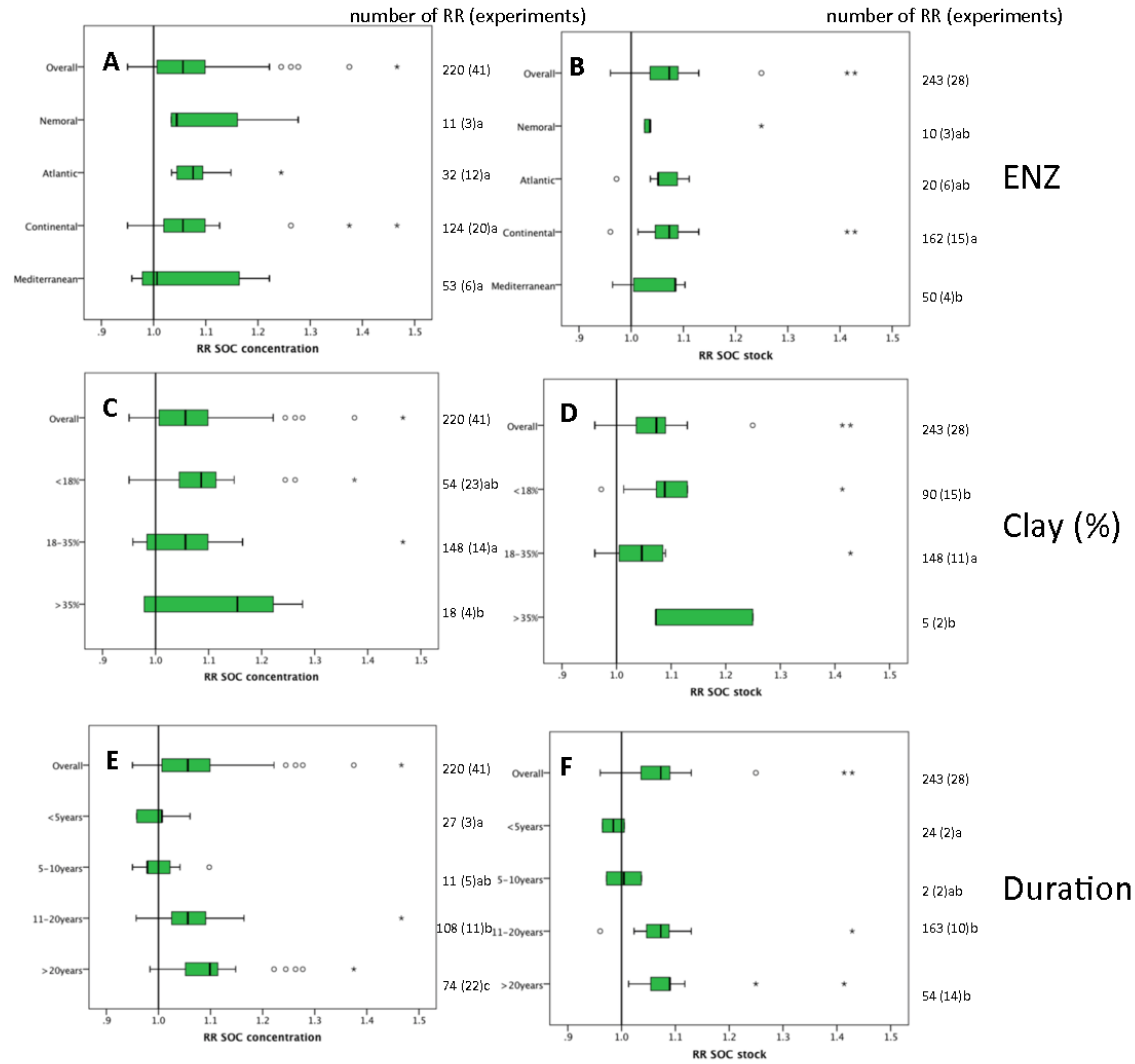


Figure 3

