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## **Crops for increasing soil organic carbon stocks - a Global Meta Analysis**

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20 **Abstract**

21 Quantifying the ability of plants to store atmospheric inorganic carbon (C) in their biomass  
22 and ultimately in the soil as organic C for long duration is crucial for climate change  
23 mitigation and soil fertility improvement. While many independent studies have been  
24 performed on the transfer of atmospheric C to soils for single crop types, the objective of this  
25 study was to compare the ability of crops which are the most commonly found worldwide to  
26 transfer C to soils, and the associated factors of control. We performed a meta-analysis of 227  
27 research trials, which had reported C fluxes from plant to soil for different crops. On average,  
28 crops assimilated 4.5 Mg C ha<sup>-1</sup> yr<sup>-1</sup> from the atmosphere with values between 1.7 Mg C ha<sup>-1</sup>  
29 yr<sup>-1</sup>, for barley (*Hordeum vulgare*) and 5.2 Mg C ha<sup>-1</sup> yr<sup>-1</sup> for maize (*Zea mays*). 61% of the  
30 assimilated C was allocated to shoots, 20% to roots, 7% to soils while 12% was respired back  
31 into the atmosphere as autotrophic respiration by plants. Maize and ryegrass (*Lolium perenne*)  
32 had the greatest allocation to the soil (1.0 Mg C ha<sup>-1</sup> yr<sup>-1</sup> or 19% total assimilation), followed  
33 by wheat (*Triticum aestivum*). 0.8 Mg C ha<sup>-1</sup> yr<sup>-1</sup>, 23%) and rice (*Oryza Sativa*, 0.7 Mg C ha<sup>-1</sup>  
34 yr<sup>-1</sup>, 20%). C allocation to the soil positively correlated to C allocation to roots C (r=0.33,  
35 P<0.05) while correlations between on the one hand shoot and root biomass and on the other  
36 hand C allocation to shoots were not significant. The question of the long -term stability of the  
37 C transferred to soils remains unanswered.

38 **Keywords:** Carbon transfer, C assimilation, plant C, C labeling, C flux

39

## 40 **Introduction**

41 In 2015, 192 countries ratified the Paris Agreement at COP21 in Paris to limit the rise of  
42 global air temperature to 2°C above pre-industrial levels by the end of this century (Minasny  
43 et al. 2017). At that occasion, the 4 per mille Initiative: Soils for food security and climate  
44 (4p1000) was launched by the French government with the aspiration to transfer atmospheric  
45 carbon (C) to soils for a net increase in soil organic carbon (SOC) stocks (also termed soil  
46 carbon sequestration, e.g. Chenu et 2019) by 0.4% per year (Minasny et al. 2017). The  
47 Initiative envisaged that atmospheric C sequestration into soils would yield spillover benefits  
48 such as reduced increase of global temperature, improved soil fertility; favorable soil  
49 structure, high soil biodiversity, and reduced risk of soil erosion will accrue (Lal 2016) to  
50 sustain higher crop productivity.

51 However, some practices proposed by Paustian et al. (2016) to meet the 4p1000 objectives,  
52 such as reduced tillage and land use conversion, are subjects of debate. For example, it has  
53 been argued that reduced tillage only cause redistribution of SOC within the soil profile with  
54 no net gain (Dimassi et al. 2014; Haddaway et al. 2017), while land use conversion from  
55 cropland to grassland or forest can have negative implications for SOC stocks and food  
56 security. Furthermore, there is a high tendency to rely on best agronomic practices for  
57 increasing SOC stocks, while neglecting the effects of plants despite abundant evidence that  
58 genetic variation, especially in root traits, influences C allocation in terrestrial ecosystems  
59 (Warembourg et al. 2003).

60 Carbon sequestration into soils is influenced by equilibrium C carrying capacity of the soil,  
61 the vegetation it supports and the attendant climatic factors (Gupta and Rao, 1994; Lal, 2004).  
62 Plants play a pivotal role in the global cycle because more than 10% of the carbon dioxide  
63 (CO<sub>2</sub>) in the atmosphere is recycled through photosynthesis (Raich and Potter, 1995). After  
64 photosynthesis, plants deposit organic C into the soil via exudation and biomass C

65 incorporation into the soil and a net increase in the soil C stocks is realized when the amount  
66 of C deposits are higher than C losses through microbial decomposition and root respiration  
67 (Fearnside and Barbosa, 1998). Plant C is either incorporated as structural C, released as  
68 exudates or respired as CO<sub>2</sub> (Ostle et al. 2003). These processes vary with crops' genetic  
69 characteristics, leading to potential differences in C fluxes to soils (Kuzyakov and Domanski  
70 2000). Yet there is little empirical analysis on how crops differ in their ability to enhance SOC  
71 stocks (Wegener et al. 2015). The first step for assessing the ability of crops to sequester C in  
72 terrestrial ecosystems lies in the evaluation of the C fluxes to the different pools: shoots, roots  
73 and soil.

74 There have been concerted efforts to understand C fluxes in the plant/soil system (e.g. Remus  
75 and Augustin 2016; Studer et al. 2014). Carbon fluxes are commonly estimated by measuring  
76 changes in SOC stocks over time (e.g. Hemminga et al. 1996). However, this method lacks  
77 precision when little changes in SOC stocks occur and is unable to distinguish between the  
78 preexistent and "new" SOC (e.g. Remus and Augustin 2016). Isotopic C labeling, where C 12  
79 atoms are replaced with either C 13 or 14 atoms, facilitate the quantification of C fluxes from  
80 atmosphere to soil through plants (Studer et al. 2014). Based on C labelling, it has been  
81 reported that plants transfer from 30 to 50% of their photosynthetic C below ground  
82 (Buyanovsky and Wagner 1997). Furthermore, C labelling has proven that the translocation of  
83 C to roots may occur immediately after C assimilation in leaves with up to 10% of the  
84 photosynthetic C being detected in roots within 2 hours (Kaštovská and Šantrůčková 2007).

85 Carbon assimilated by plants is allocated to above ground (shoots and reproductive organs)  
86 and below ground (roots) biomass depending on plant genetic constitution (de Neergaard and  
87 Gorissen 2004), plant growth pattern, environmental conditions and interactions among these  
88 factors (Rangel-Castro et al. 2005). However, it is the root C fluxes, which are particularly  
89 important for increasing SOC stocks because root tissues and/or root exudates are in

90 immediate contact with the decomposer community and the mineral phase, thus leading to  
91 lower mineralization rates as compared to shoot-derived C (Rasse et al. 2005). Labile C inputs  
92 such as those derived from above ground biomass are potentially easily decomposed, leading  
93 to losses of the total plant C stock of 15–45% in case of perennial plants and 27–60% in  
94 annuals (e.g. Warembourg and Paul 1977; Swinnen et al. 1995a).

95 Several compilations of individual studies have been performed to identify the trends in SOC  
96 dynamics (e.g., Guo and Gifford, 2002; Poeplau et al. 2011; Don et al. 2011). From Guo and  
97 Gifford (2002), we learn that the conversion of natural vegetation to cropland is detrimental to  
98 SOC stocks with a worldwide average loss in the 0-0.3m soil layer of 42% from native forest  
99 and of 59% from grassland. From this meta-study we also learn that afforestation of cropland  
100 can increase SOC stocks by as much as 50%, with Laganière et al., (2010) indicating greatest  
101 increase by using broadleaf tree species as compared to coniferous species. Meta-studies on  
102 land management impact on SOC stocks have also been performed. Poeplau and Don (2015)  
103 using 139 plots worldwide showed the potential of cover crops to increase SOC stocks in the  
104 first 0.2 m of the soil to be of  $0.32 \pm 0.08 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$  or about 0.5% or 5p1000. The study  
105 by Ugarte et al (2014) using data from 55 peer-reviewed studies showed a 9% average  
106 increase of SOC stocks in the 0-0.3 m layer using diversified crop rotations and conservation  
107 systems as compared to the conventional controls, a result confirmed by Alison et (2017). The  
108 increase was 32% by using a combination of chemical and organic fertilization (Han et al.,  
109 2016) as compared to no fertilization and Shi et al (2018) pointed to a 18% increase in SOC  
110 stocks using agroforestry under subtropical climate, all these studies considered the soil to a  
111 depth of 0.3m.

112 While several individual studies worldwide have been published on the fluxes of atmospheric  
113 C to soils on one or several crops, these data have not been compiled yet and the global trends  
114 are still unknown.

115 This study aimed at compiling multiple trials across the world that quantified C fluxes from  
116 the atmosphere to the soil during the growing cycle using C labelling. The hypothesis behind  
117 this study is that some crops might be more efficient than others to build SOC and might thus  
118 be promoted.

119

## 120 **Materials and Methods**

### 121 **Meta analysis**

122 The study is a meta-analysis based on data collated from isotopic C enrichment experiments  
123 conducted across the world. The data was obtained from peer-reviewed journal articles  
124 published between 1985 and 2016. The journal articles were obtained from academic  
125 databases (Google Scholar, Refseek, Science Direct, SciFinder, Scopus, Springer Link and  
126 Web of Science) using key words and phrases, singly and/or in combination, such as “isotopic  
127 pulse labelling”, “C allocation”, “plant carbon sequestration”, “rhizodeposition” and  
128 “plants/soil/microbial respiration”. The literature survey considered studies reporting the  
129 allocation of C to plant shoots and roots, soil pools and proportions of the respired C as either  
130 percentages or absolute quantities. Thirty-three journal articles (Table 1) detailing different  
131 studies were obtained using the above criteria providing 227 observations from different  
132 experiments, globally (Fig. 1). A database was constructed to capture the names of authors,  
133 year of publication, type of C isotope, type of crop, quantitative information on C allocation  
134 variables and the controlling factors (Supplemental Table).

135

### 136 **The study variables, calculations and statistical analysis**

137 This study simplified the soil-plant system within three pools, namely, plant shoots, plant  
138 roots, and soil. Information on C allocation to shoots ( $S_c$ ), to roots ( $R_c$ ), soil allocated C ( $S_{oc}$ )  
139 and respiration from the soil ( $RE_c$ ) (defined in Table 2) were collated from the different

140 studies. All these variables were estimated using the pulse labelling method where ambient  
141  $^{12}\text{CO}_2$  was partially replaced by  $^{13}\text{CO}_2$  or  $^{14}\text{CO}_2$  for short durations. After harvest, plant parts  
142 (shoots and roots) as well as soil samples (collected from the pots in the case of glasshouse  
143 experiments or from the undisturbed soil in the case of field trials) were oven-dried ( $70^\circ\text{C}$ ),  
144 ground to 2 mm and analyzed for total C,  $^{13}\text{C}$  or  $^{14}\text{C}$  using C analysers coupled with mass  
145 spectrometers.

146 Since the experiments differed as to the duration of pulse labelling, as to the concentration of  
147 labelled  $\text{CO}_2$  and as the concentration of total  $\text{CO}_2$ , the data of C allocation were normalized  
148 and transformed into single unit for unbiased comparison. Normalization was done by  
149 dividing the reported C allocations by the respective  $\text{CO}_2$  concentration used during  
150 enrichment, duration of exposure during enrichment or the duration of that particular  
151 experiment, thus assuming the existence of linear relationship between the intensity of C  
152 fluxes in the atmosphere-plant-soil system and these variables. Moreover, in order to compare  
153 the crops' potential to transfer C to soils over an entire year, the data in different units were  
154 reported on a yearly basis by summing the fluxes observed during the growing months (i.e.  
155 few months in case of maize vs 12 months for permanent grasses), and harmonized as  
156  $\text{Mg C ha}^{-1} \text{ yr}^{-1}$ . Finally, the variations between field and greenhouse results were tested using  
157 the independent two-sample t-test at 95% confidence level using Genstat 18<sup>th</sup> edition (Payne  
158 et al. 2017). The parameters measured under field conditions were tested for normality and  
159 treated as independent samples from the greenhouse data and the two samples were regarded  
160 as heteroscedastic samples during the procedure for t-test (Yang et al 1992).

161 Finally, the sample size for each variable was determined and stratified by crop type and  
162 environmental variable, namely soil texture, soil organic carbon content (SOCc) and average  
163 air temperature (Table 3). Summary statistics for the variables were derived including  
164 minimum, maximum, median, standard deviation (SD), skewness, 25<sup>th</sup> quartile (Q1) and 75<sup>th</sup>



165 quartile (Q3), kurtosis and coefficient of variation. Afterwards, the data were summarized  
166 using box plots to elucidate the variability and distribution after checking out the outliers.  
167 Boxplots are presented for six major staple crops due to scarcity of data in the other crops.  
168 Bivariate and multivariate analyses, using Spearman rank correlations and principal  
169 component analysis (PCA), respectively, were conducted to depict the general relationships  
170 between C variables and some controlling factors.

171

172

## 173 **Results**

### 174 **Variability in C Allocation to plant parts**

175 Table 4 presents the statistics of biomass and C allocation to the different plant parts from the  
176 field and greenhouse trials. As shown by the statistical t test (Table 4), there was no  
177 significant differences between field and greenhouse trials for all study variables, except for  
178 root biomass (Rb), which was about two times higher under field conditions than in  
179 greenhouses (36 vs 16 MgCha<sup>-1</sup>).

180 The average C allocation to shoots ranged from 0.20 Mg C ha<sup>-1</sup> yr<sup>-1</sup> recorded by Swinnen et  
181 al. (1995a) for barley in the Netherlands to 5.60 Mg C ha<sup>-1</sup> yr<sup>-1</sup> for wheat in Spain (Aljazairi et  
182 al. 2015); the mean shoot C flux for all plant species was 2.48± 0.09 Mg C ha<sup>-1</sup> yr<sup>-1</sup>. The mean  
183 C allocation to roots was 1.0± 0.04 Mg C ha<sup>-1</sup> yr<sup>-1</sup> with a lowest of 0.1 Mg C ha<sup>-1</sup> yr<sup>-1</sup>  
184 calculated for sub-tropical wheat in Australia (Fan et al. 2016) and a highest of 2.8 Mg C ha<sup>-1</sup>  
185 yr<sup>-1</sup> calculated for ryegrass in a temperate region of the USA (Butler et al. 2004). The lowest  
186 total C allocation was 0.2 Mg C ha<sup>-1</sup> yr<sup>-1</sup> by wheat, while the highest was 22.1 Mg C ha<sup>-1</sup> yr<sup>-1</sup>  
187 by *Kobresia* spp. grass in temperate China (Wu et al. 2010). Mean C loss from soil as CO<sub>2</sub>  
188 (autotrophic plus heterotrophic respiration) was 0.63±0.30 Mg C ha<sup>-1</sup> yr<sup>-1</sup>. Greenhouse grown  
189 soyabean had the highest C emissions of 1.8 Mg C ha<sup>-1</sup> yr<sup>-1</sup> (Harris et. al. 1985). An average  
190 of 0.90±0.05 Mg C ha<sup>-1</sup> yr<sup>-1</sup> was allocated to soils with a maximum of 3.00 Mg C ha<sup>-1</sup> yr<sup>-1</sup>  
191 found for temperate maize in the USA (Holland et al. 1995). Environmental factors also  
192 showed wide variability. The soil clay content ranged from 6.1 to 36.0%, while the SOCc  
193 ranged from 2.70 to 37.00 g C kg<sup>-1</sup>. Temperatures varied from 5°C in the Netherlands  
194 (Swinnen et al. 1995a) to 34.7°C in Spain (Fernández et al. 2003).

195

### 196 **Crop type impact on C allocation to shoot and roots**

197 Figure 2 shows the variations in C allocation in the different pools (shoot, root, and soil) of  
198 the plant-soil system as function of crop type. The highest mean C allocation to shoots was  
199 observed in maize ( $4.10 \pm 0.12 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ), which was 44% higher than for ryegrass  
200 ( $2.85 \pm 0.21 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ), which ranked second, and 91% higher than in barley ( $2.15 \pm 0.24$   
201  $\text{Mg C ha}^{-1} \text{ yr}^{-1}$ ) with the lowest C allocation. The C allocation to shoot in wheat ( $2.52 \pm 0.20$   
202  $\text{Mg C ha}^{-1} \text{ yr}^{-1}$ ) and rice ( $2.30 \pm 0.15 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ) were not significantly different. Ryegrass  
203 had at least 17% higher C allocation to shoots as compared to all the other crops except  
204 maize. The highest mean C allocations to roots were found in ryegrass ( $1.50 \pm 0.18 \text{ Mg C ha}^{-1}$   
205  $\text{yr}^{-1}$ ), followed by rice ( $1.48 \pm 0.17 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ) and maize ( $1.40 \pm 0.21 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ), but  
206 with differences being not significant at  $P < 0.05$  (Fig. 2b). In contrast, barley exhibited  
207 significantly ( $p \leq 0.05$ ) lower C allocation to roots as compared to all the other crop species,  
208 while wheat and soyabean had intermediary C allocation to roots.

209

### 210 **Crop type impact on C allocation to the soil**

211 Figure 3 compares the C allocation to the soil by the selected crops to the C allocation in the  
212 different plant parts, as a means to assess crop efficiency in allocating atmospheric C into  
213 soils. Soyabean had the largest proportion of C allocated to the soil as compared to the whole  
214 plant (ratio of  $0.32 \pm 0.07$ , fig. 3a), which means that the amount of C recovered in the soil  
215 during the growing season is about a third of that recovered in the plant. Barley was the  
216 second most efficient crop because it transferred  $0.29 \pm 0.06$  units of C per unit of C fixed by  
217 the plant. Wheat, maize and rice showed similar efficiencies in terms of C transfer to the soil  
218 relative to the total C allocated in the plant (ratios between 0.18 and 0.20).

219 C allocation to the soil relative to C allocation to shoots exhibited a similar trend with  
220 soyabean having the highest efficiency followed by barley (Fig. 3b). In contrast, barley and  
221 wheat had the highest C allocation to soils as compared to roots (ratio of 1.22, fig. 3b). The

222 least C allocation to soils per unit C allocation to roots was recorded in rice with a ratio of  
223 0.48. Maize and soybean showed non-significant difference with means of 0.96 and 0.98,  
224 respectively. Figure 3d shows the C allocation to soils relative to C emission from the soil as  
225 CO<sub>2</sub> for the different crops. The highest ratio was observed for ryegrass (1.88±0.17) followed  
226 by wheat (1.48±0.11), maize (1.30±0.13) and barley (1.00±0.23).

227 Figure 4 compares C allocation in the plant to C respiration from the soil. Ryegrass lost the  
228 least amount of C through respiration relative to total plant C allocation (ratio of 0.11±0.01,  
229 fig. 4a). For soyabean and barley, C respiration constituted above 40% of plant C allocation  
230 while for the rest of the crop species this proportion was less than 20%. Soyabean had also the  
231 highest ratio of respired C to shoot C allocation (0.85±0.13) which was 24% higher than for  
232 ryegrass and with wheat showing the least ratio (Fig. 4b). Respired soil C as a fraction of C  
233 allocation in roots was the highest barley and soyabean with 1.49±0.26 and 1.38±0.17,  
234 respectively (Fig. 4c).

235

## 236 **Variations in plant C allocation with soil properties and climate**

### 237 **Soil texture**

238 Figure 5 shows the variations in C allocation in response to soil clay content. For clayey soils,  
239 the mean C allocation to shoots was 2.36±0.23 Mg C ha<sup>-1</sup> yr<sup>-1</sup> (Fig. 5a), which was 13% lower  
240 than that of loam textured soils (2.70±0.25 Mg C ha<sup>-1</sup> yr<sup>-1</sup>) with the widest variability (values  
241 between 0.5 and 4.6 Mg C ha<sup>-1</sup> yr<sup>-1</sup>). There was a decrease in root C allocation from clayey  
242 and loamy (1.30±0.13; 1.36±0.16 Mg C ha<sup>-1</sup> yr<sup>-1</sup>) to sandy soils (0.91 Mg C ha<sup>-1</sup> yr<sup>-1</sup>) (Fig.  
243 5b). In contrast, soil respiration significantly decreased by 60% from sandy (0.75±0.12 Mg C  
244 ha<sup>-1</sup> yr<sup>-1</sup>) to clayey (0.47±0.03 Mg C ha<sup>-1</sup> yr<sup>-1</sup>) and sandy soils (0.46±0.04 Mg C ha<sup>-1</sup> yr<sup>-1</sup>), with  
245 the differences between clayey and sandy soils being not significant at P<0.05 (Fig. 5c).

246 The amount of isotopic C detected in the soil significantly and positively correlated with soil  
247 clay content ( $r=0.46$ ,  $p<0.05$ ). Figure 5d shows a general increase for isotopic C from  
248  $0.43\pm 0.09$  Mg C ha<sup>-1</sup>yr<sup>-1</sup> in sandy soils to  $1.04\pm 0.07$  Mg C ha<sup>-1</sup> yr<sup>-1</sup> under loamy and  
249  $1.08\pm 0.06$  Mg C ha<sup>-1</sup> yr<sup>-1</sup> under clayey soils. The C detected in clay soils was nearly 150%  
250 higher than soil C fluxes under sandy soils.

251

### 252 **Soil carbon content**

253 SOC content exhibited a significant ( $p>0.05$ ) and positive correlation with root C allocation  
254 ( $r=0.44$ ) and with soil respiration ( $r=0.20$ , Table 5). Root C allocation was 33% higher from  
255  $0.79\pm 0.08$  Mg C ha<sup>-1</sup> yr<sup>-1</sup> under low SOCc to  $1.07\pm 0.08$  Mg C ha<sup>-1</sup> yr<sup>-1</sup> under medium SOCc  
256 soils (Fig. 6b). Root C was  $1.01$  Mg C ha<sup>-1</sup> yr<sup>-1</sup> at higher SOCc, which did not correspond to a  
257 significant difference at  $p>0.05$ . Soil C allocation was with  $1.01\pm 0.16$  Mg C ha<sup>-1</sup> yr<sup>-1</sup> the  
258 highest under medium SOCc and the lowest under low SOCc ( $0.84\pm 0.06$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>).  
259 Finally, soil respiration did not significantly differ for all study SOCc classes (Fig. 6d).

260

### 261 **Climate**

262 Figure 7a shows that shoot C allocation was about 8% lower ( $2.32\pm 0.23$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>) under  
263 cool climate than under warm conditions ( $2.51\pm 0.13$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>) and was the lowest  
264 ( $2.18\pm 0.08$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>) under hot temperatures. The difference between cool and warm  
265 climates was not significant. The weak negative correlation between temperature and shoot C  
266 fluxes was also revealed by the bivariate correlations (Table 5). In contrast, root C allocation  
267 and temperature were positively correlated (Table 5). An increase of over 53% in root C  
268 allocation was observed from  $0.75\pm 0.14$  Mg C ha<sup>-1</sup> yr<sup>-1</sup> under cool to  $0.99\pm 0.12$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>  
269 under warm temperatures, while there was a sharp increase of 200% from warm to hot  
270 temperatures ( $1.51\pm 0.15$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>) (Fig. 7b). The association between temperature and

271 soil respiration was relatively strong and positive ( $r=0.34$ ;  $p\leq 0.05$ ) (Table 5). Carbon  
272 emissions due to respiration under warm ( $0.63\pm 0.01$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>) and hot ( $0.62\pm 0.02$  Mg C  
273 ha<sup>-1</sup> yr<sup>-1</sup>) temperatures were similar, while they were significantly lower under cool  
274 temperatures ( $0.54\pm 0.05$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>) (Fig. 7c). Soil C allocation exhibited a negative  
275 correlation with temperature (Table 5, Fig. 7d). However, the differences in soil C allocation  
276 between cool ( $0.90\pm 0.08$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>) and warm ( $0.86\pm 0.05$  Mg C ha<sup>-1</sup> yr<sup>-1</sup>) temperature  
277 zones were not significant and ranged between  $0.58\pm 0.06$  (Fig. 7c).

278

### 279 **Multivariate analysis**

280 Principal component analysis (PCA) was conducted using the selected variables and data  
281 from all crop species. The first two principal components (Fig. 8) accounted for 68% of the  
282 data variability. The first principal component (Axis 1), which accounted for 40% of data  
283 variability, correlated the most with SOCc with positive coordinates. Since soil respiration  
284 had positive coordinates on Axis 1, it can be inferred that soil respiration increased with  
285 increasing SOCc. There was also a trend for soil respiration to positively correlate with C  
286 allocation in plant and in shoots. Principal component 2 (Axis 2), accounting for 28% of the  
287 variability in data, correlated the most with the shoot and plant biomass with positive  
288 coordinates, and air temperature and soil clay content with negative coordinates. The trend  
289 was thus for shoot and plant biomass to decrease with increase in air temperature and soil clay  
290 content. Moreover, as C allocation to soils and to roots showed negative coordinates on  
291 Axis 2, the trend was also for more C to be allocated to roots and to soils under clayey and  
292 warm conditions than under sandy and loamy soils of cooler climates. Interestingly, C inputs  
293 to roots and to soils appeared to decline with increasing shoot biomass.

294

## 295 **Discussion**

### 296 **The impact of crop species on C assimilation from atmosphere to shoots and roots**

297 The wide variations in atmospheric C allocation to shoots from 0.4 to 5.6 Mg C ha<sup>-1</sup> yr<sup>-1</sup> was  
298 expected and is likely to result from variable environmental conditions, plant growth pattern  
299 and internal metabolism which are under genetic control (Staddon et al. 2004; Warembourg et  
300 al 2003). Maize exhibited a significantly higher assimilation of atmospheric C into shoots  
301 than ryegrass, which confirmed previous reports by Pausch and Kuzyakov (2017) and  
302 Atkinson et al. (2014). The differences in shoot C fluxes among annual crops could be partly  
303 due to variations in efficiency in C capture and internal C metabolism. For instance, maize has  
304 a higher leaf area and C4 photosynthetic pathway which render it more efficient in  
305 atmospheric C capture than C3 crops (wheat or rice), while its high concentration of lignin  
306 and hemicellulose result in the retention of more C in the shoots (Adapa et al. 2009; Li et al.  
307 2013).

308 The flux of C to roots in maize, rice and ryegrass was above 1.0 Mg C ha<sup>-1</sup> yr<sup>-1</sup> across all crop  
309 types, a result that is in agreement with the investigations by Huang and Johnson (1995) and  
310 Mathew et al. (2017). Root C allocation are influenced by genetic variations and/or growth  
311 habits with for instance ryegrass because of perennial growth storing a larger proportion of  
312 the assimilated C in its roots as compared to annual crops (Purdy et al. 2015). The high  
313 amount of C assimilated in maize roots is related to its high photosynthetic capacity which  
314 avails large amount of assimilates for translocation to the roots (Amanullah and Stewart 2013;  
315 Pausch and Kuzyakov 2017) after meeting demand in the above ground biomass (Ludewig  
316 and Flügge 2013). In case of rice, the high amount of C allocated to roots results from the  
317 plant's response to maintain root development under hypoxic conditions (Huang and Johnson  
318 1995).

319

## 320 **The link between plant C fluxes and C transfer to the soil**

321 The existence of a significant correlation between root C allocation and C allocation to the  
322 soil ( $r=0.38$ ;  $p\leq 0.05$ , table 5) is supported by prior knowledge showing that root derived C  
323 constitutes a substantial proportion of SOC (Rasse et al. 2005). Root C contributes to SOC  
324 through various ways, e.g., provision of C exudates which are eventually stabilized in the soil,  
325 physical protection of soils against erosion, formation of associations with mycorrhizae for C  
326 immobilization in the soil and providing exchange site for chemical interactions between  
327 plant and soil ions (Rasse et al. 2005). Intuitively, higher C allocation to roots increases the  
328 potential for C transfer to soils as more root exudates are released into the soil.

329 Crop species differ in the amounts of C allocation to the roots and in their root characteristics,  
330 which appeared in the present study to subsequently result in differences in the amount of C  
331 transferred to the soil by the different crop species. Ryegrass and rice exhibited high higher C  
332 allocation to the roots and to the soil, while maize and wheat showed high C allocation to soil  
333 ( $>0.8 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ ) despite low root C allocation. The latter could point to the existence of  
334 mechanisms of regulation of C transfer to soils. Such mechanisms are beyond the scope of  
335 this paper but understanding these is required to identify crops for SOC sequestration.

336 It was also interesting to observe that soyabeans had low C allocation to the soil ( $0.64 \text{ Mg C}$   
337  $\text{ha}^{-1} \text{ yr}^{-1}$ ) despite having high root C allocation. This points to the relative inefficiency of  
338 legumes to build SOC. Microbial respiration, which returns C to the atmosphere as shown by  
339 the high Rec (Fig. 2d), can be implicated in the low C sequestration potential of legumes. In  
340 the short term, soil C sequestration under annual crops such as maize may be higher than  
341 perennials such as ryegrass because C exudation below ground in annual crops peaks earlier  
342 during plant development than in perennials (Pausch and Kuzyakov 2017). Conversely,  
343 ryegrass is likely to contribute more biochemically stable C to soils through root turnover  
344 rather than exudation (Menichetti et al. 2015; Mota et al. 2010). Chemical, physical and



345 biochemical processes influence the amount of C stabilized in the soil. For instance plant  
346 matter with low C:N ratio, like soyabean shoots are easily decomposed by microbes to  
347 become SOC as compared to crop residues with high C:N such as from cereals (Abiven et al.  
348 2009).

349 From Hütsch et al. (2002) we learn that only up to 5% of the C assimilated by plants is  
350 eventually stabilized in the soil after accounting for respiration. Based on estimations after  
351 harvest in the current study, C transfer to the soil reached 32% of net plant total C  
352 assimilation in soyabean, followed by barley (28%) and wheat (23%), while values for maize,  
353 ryegrass and rice reached 19% of their assimilated C to the soil. The question of the longer  
354 term stabilization of this newly assimilated SOC remains unanswered. There is also a need to  
355 conduct more investigations to assess the longer term impacts of rhizodeposition of energy-  
356 rich substrates in deep soil horizons on the mineralization of pre-existent “old” soil organic  
357 matter, by a process called rhizosphere priming effect (e.g. Fontaine et al., 2004; Shahzad et  
358 al, 2018).

359

### 360 **The link between C assimilation in the soil and soil CO<sub>2</sub> emissions**

361 The study showed no significant correlation between C assimilation in the soil and soil CO<sub>2</sub>  
362 emissions suggesting that addition of C does not necessary enhance C losses through  
363 respiration in the short term, which may be explained by a possible mechanism that offers a  
364 relatively higher protection of the newly assimilated C. There were large differences in C  
365 emissions from soils with, for example, soyabeans emitting 1.12 Mg C ha<sup>-1</sup> yr<sup>-1</sup> while ryegrass  
366 grass emitted significantly lower amounts (0.49 Mg C ha<sup>-1</sup> yr<sup>-1</sup>). The high amount of C  
367 emission under soyabean may be explained as mentioned above by a low C:N ratio and  
368 associated high microbial respiration (Schmitt et al. 2013) as compared to cereals (Pausch and  
369 Kuzyakov 2017). The higher soil CO<sub>2</sub> emissions under maize (0.9 Mg C ha<sup>-1</sup> yr<sup>-1</sup>) are most

370 likely because of high hemicellulose-content biomass (Adapa et al. 2009; Li et al. 2013) and  
371 low C:N ratio as compared to barley and wheat (Velthof et al. 2002). Despite higher soil CO<sub>2</sub>  
372 emissions, maize exhibited a higher C allocation to soils than wheat, barley and rice showing  
373 that it is more efficient in photosynthesis (Amanullah and Stewart 2013) than the other crops.  
374 This shows that soil C accumulation can still be driven by root C allocation provided they are  
375 high enough to offset soil CO<sub>2</sub> emissions. The foregoing indicates that maize and ryegrass had  
376 superior ability for C allocation into the soil than the other plant species, while wheat  
377 appeared to be the most efficient among the winter crops such as barley.

378

### 379 **The effect of environmental conditions on C allocation into soils**

380 The results pointed to a lack of significant impact of the type of experiment performed (field  
381 vs glasshouse) on the study variables, except for root biomass which was about two times  
382 higher under field conditions (with mean of 36 MgCha<sup>-1</sup>) compared to the greenhouse (16  
383 MgCha<sup>-1</sup>). Such a lack of significant differences is indicative of the absence of major shifts in  
384 the environmental conditions at glasshouses as compared to fields. Moreover, the greater root  
385 biomass under field conditions might be explained by the fact that under field conditions the  
386 roots have more room to growth as compared to greenhouse where the root zone is  
387 constrained by the pot size.

388 The positive association between soil C sequestration and clay content ( $r=0.46$ ;  $p\leq 0.05$ )  
389 (Table 5) and the fact that clayey soils stabilized 200% more soil C than sandy soils (Fig. 5d)  
390 show the importance of soil clay fractions in C dynamics. Clay particles provide adsorption  
391 and aggregation sites for the intrinsic stability of C compounds and protection from microbial  
392 decomposition, which increases persistence of organic C in fine-textured soils in comparison  
393 with coarse texture soils (Hütsch et al. 2002).

394 The lack of a significant correlation between soil C sequestration and temperature was rather  
395 surprising and contrary to other study reports (e.g. Davidson and Janssens 2006; Jones et. al.  
396 2005). However, temperature may have impacted soil C indirectly by increasing soil moisture,  
397 soil CO<sub>2</sub> emissions and by promoting high C retention in the root biomass as Giardina et al.  
398 (2014) reported that high temperatures promote root C accumulation to maintain vital  
399 biological processes.

400

#### 401 **Implications of cropping systems on soil C dynamics**

402 Isotopic tracing techniques have shown that after fixation of atmospheric by plants, C  
403 allocation occurs to below ground biomass occurs within a few hours period (Gregory et al.  
404 1991). The C dynamics in the soils are immediately affected by exudation, respiration and  
405 immobilization to variable extents depending on the soil and plant characteristics. Root  
406 respiration is essential for plant growth although it results in loss of fixed C and represents a  
407 return loop for CO<sub>2</sub> back into the atmosphere. The results of this meta-analysis show that on  
408 average 7% of the atmospheric C fixed by plants will be stabilized into the soils while 12%  
409 was respired back into the atmosphere as autotrophic respiration by plants. The proportion  
410 varied with crop species. For instance, wheat allocated the highest proportion (23% total  
411 assimilation) of fixed C to the soil.

412 This study reported that maize and ryegrass could potentially deposit 1.0 Mg C ha<sup>-1</sup> yr<sup>-1</sup> into  
413 the soil, followed by wheat (0.8 Mg C ha<sup>-1</sup> yr<sup>-1</sup>), and rice (0.7 Mg C ha<sup>-1</sup> yr<sup>-1</sup>), showing that  
414 impact that different cropping systems could have on soil C dynamics depending on other  
415 factors such as agronomic practices. Qiao et al (2012) and An et al (2015) provided evidence  
416 that plants increased SOC but alluded to the effects of fertilizer application and mulching,  
417 which increased C sequestration potential in soybeans and maize. The impact of crops on soil  
418 C dynamics is also governed by the species as Fan et al (2008) reported that maize distributed

419 higher proportion of C below ground compared to faba beans although the distribution  
420 dynamics changed when the intercropping system was altered showing that C sequestration is  
421 also influenced by synergies or competition between and among crop communities. Fang et al  
422 (2016) investigated the impact of tillage practices on C sequestration and concluded that SOC  
423 stocks and agronomic functionality could not be improved by conservation tillage only. Plants  
424 were therefore the critical conduit for C sequestration into soil. Qiao et al (2012) found that  
425 soybean could potentially deposit 160 to 564 kg ha<sup>-1</sup> C season<sup>-1</sup> in China. In comparison,  
426 Mutegi et al (2011) estimated barley could contribute up to 3.4 Mg C ha<sup>-1</sup>, which was 600kg  
427 shortfall to maintain long term soil organic C in Denmark. In essence, there is overwhelming  
428 evidence to show the potential of crops in increasing C in the soil. The most important issues  
429 surrounding C allocation to soils are centered on the quantities of C sequestered, the mean  
430 residence time of the deposited C and the cost benefit of C sequestration by plants against the  
431 C emission during agricultural operations such as ploughing and fertilization.

## 432 **Conclusions**

433 Three main conclusions can be drawn from this study of 227 research trials worldwide  
434 investigating atmospheric C allocation to crop shoots, roots and to the soil:

- 435 (i) (i) Only a small fraction (about 7%) of the plant assimilated C is found in the soil  
436 after harvest with wheat showing the highest proportion (23%), followed by rice  
437 (20%), and maize and ryegrass with 19%;
- 438 (ii) (ii) The transfer of atmospheric C to the soil was the highest for maize (1.00 Mg C  
439 ha<sup>-1</sup> yr<sup>-1</sup>) followed by ryegrass (0.95 Mg C ha<sup>-1</sup> yr<sup>-1</sup>), rice (0.70 Mg C ha<sup>-1</sup> yr<sup>-1</sup>), and  
440 wheat (0.80 Mg C ha<sup>-1</sup> yr<sup>-1</sup>);
- 441 (iii) (iii) Irrespective of crop type, higher SOC was recorded under clayey soil and  
442 warmer climates.

443 Such quantitative information on C allocation by plants and to soils might be used by C  
444 models for improving crop selection and/or rotations for enhanced atmospheric C  
445 sequestration, soil fertility and crop production, from short to long term. These results could  
446 also be used in selecting crop genotypes of higher soil C sequestration potential, which could  
447 be useful in informing the breeding efforts to enhance the genetic capacity of existing crops.  
448 More is however to be done on the long term stability of the C allocated to soils and on the  
449 mechanisms involved in the C transfer from roots to its stabilization into soils. There is also a  
450 need to identify the genetic markers associated with the key traits for C allocation in the  
451 different plant parts and into the soil to further marker-assisted breeding and trait  
452 introgression into agronomically desirable genotypes that would potentiate C storage without  
453 compromising grain yield and grain quality.

454

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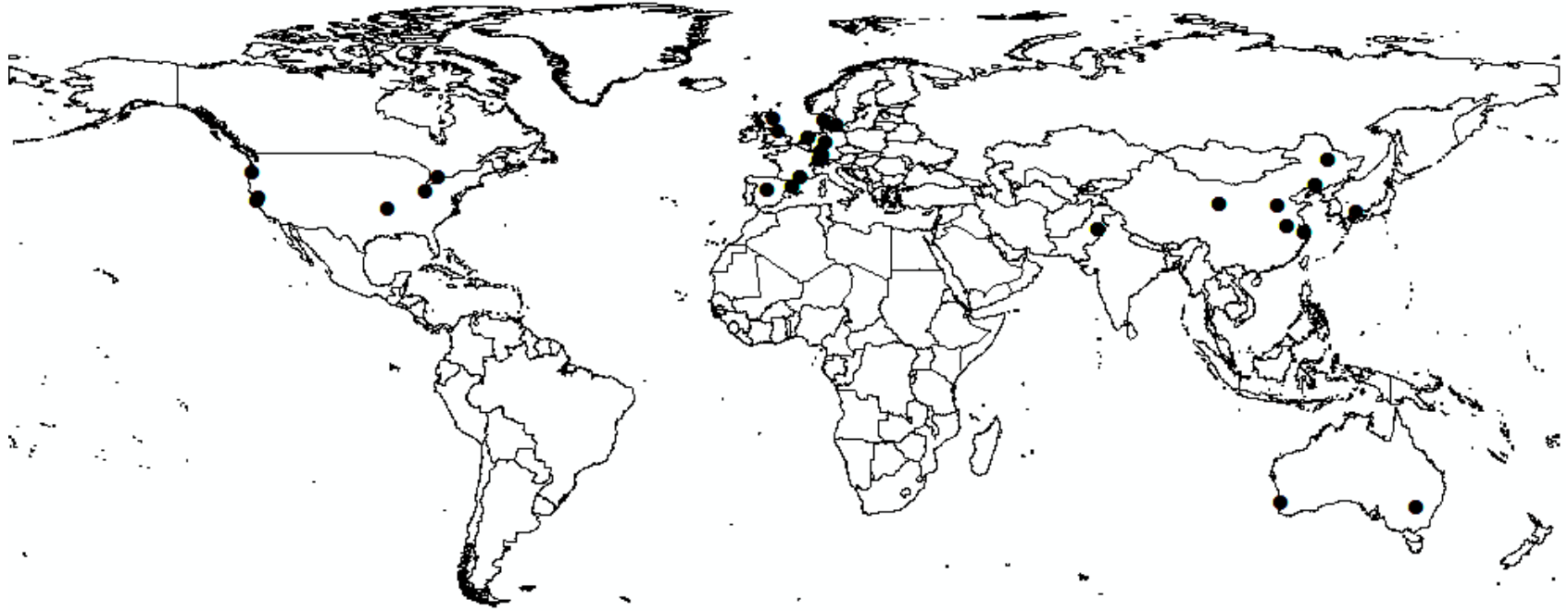
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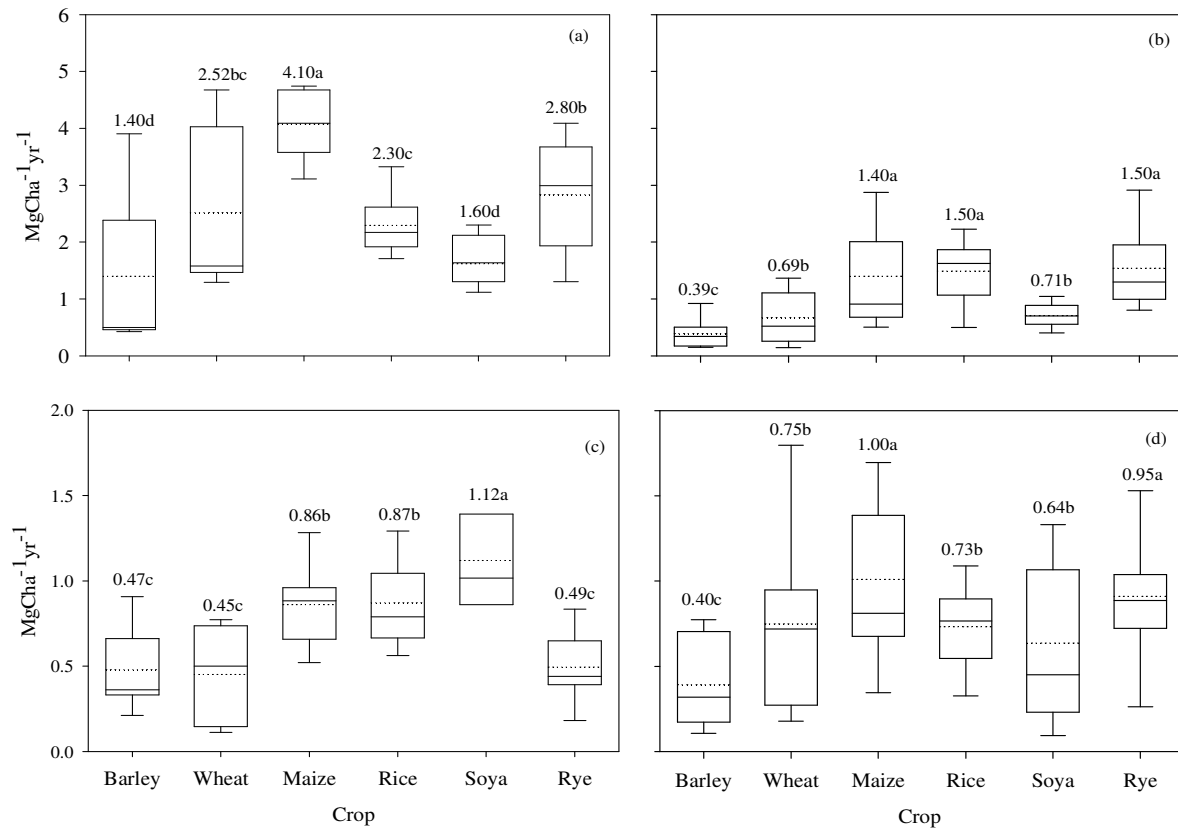
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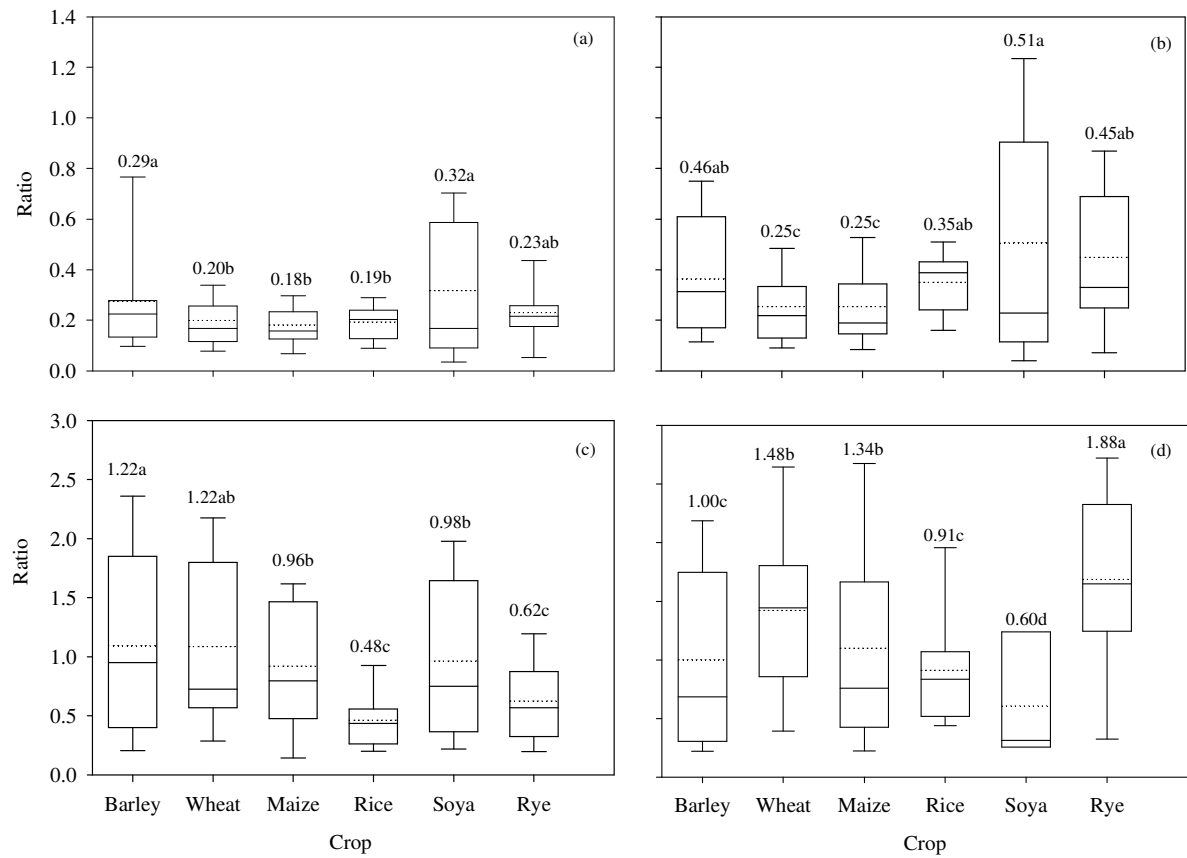


**Fig. 1** Global distribution of the study sites shown by shaded circles on the map

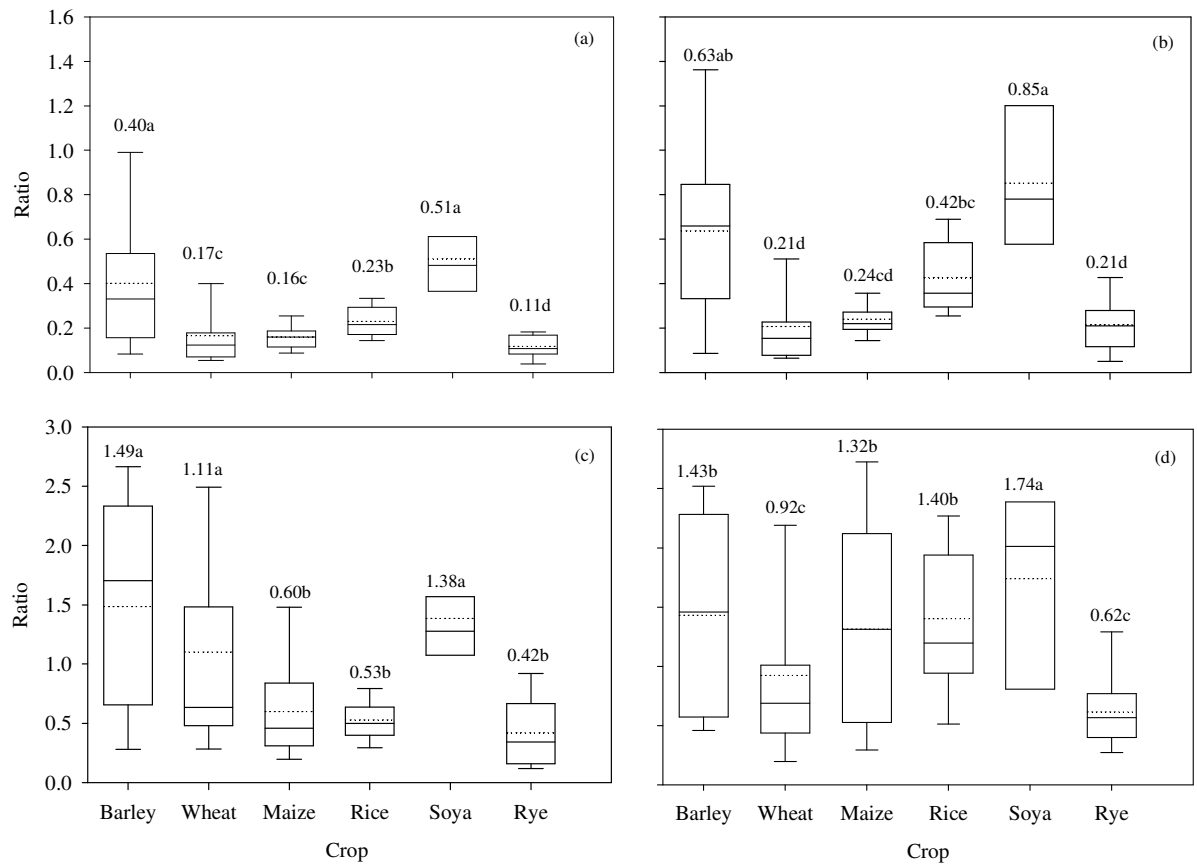


**Fig. 2** Carbon allocation into (a) Sc: shoots, (b) Rc: roots; c) REc: soil respiration and (d) SOc: C allocation to the soil; as affected by crop species. Rye=ryegrass and Soya=soyabean. Values above the top whisker represent mean values of each crop. Means followed by the same letters are not significantly different at  $p \leq 0.05$ .

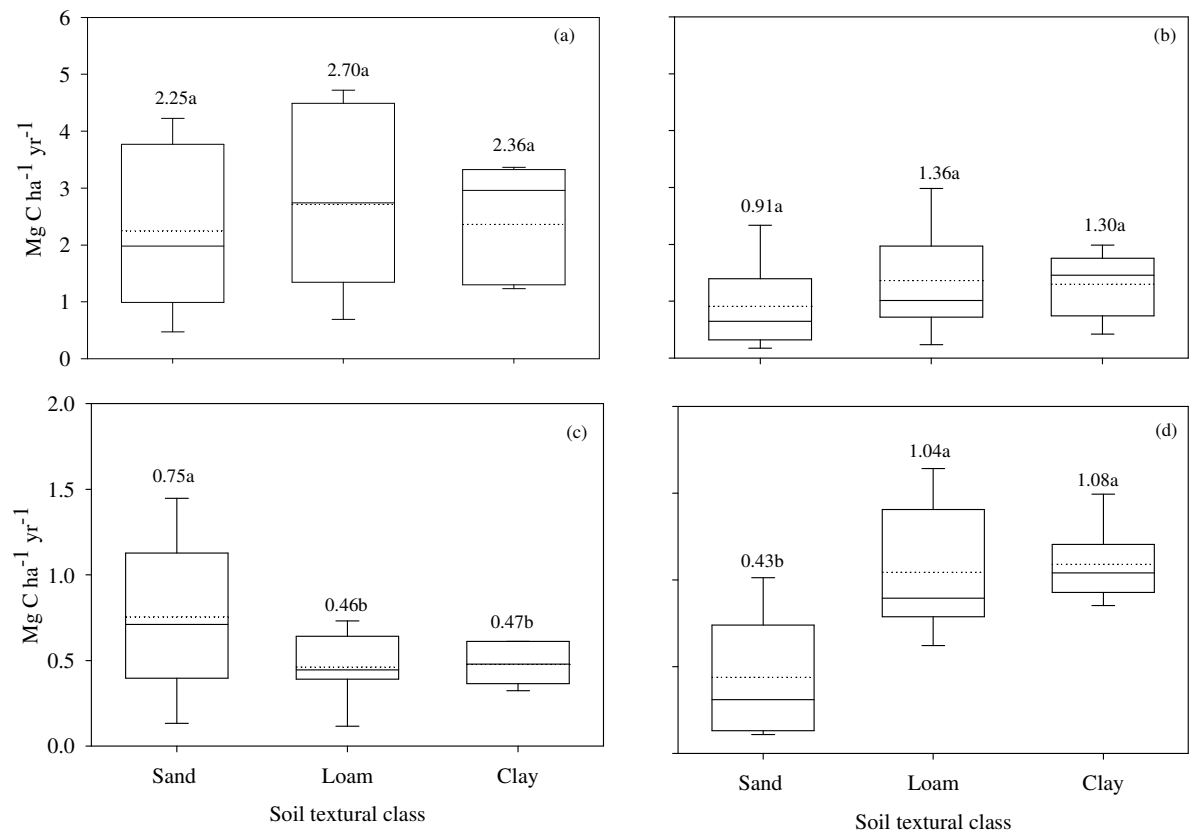




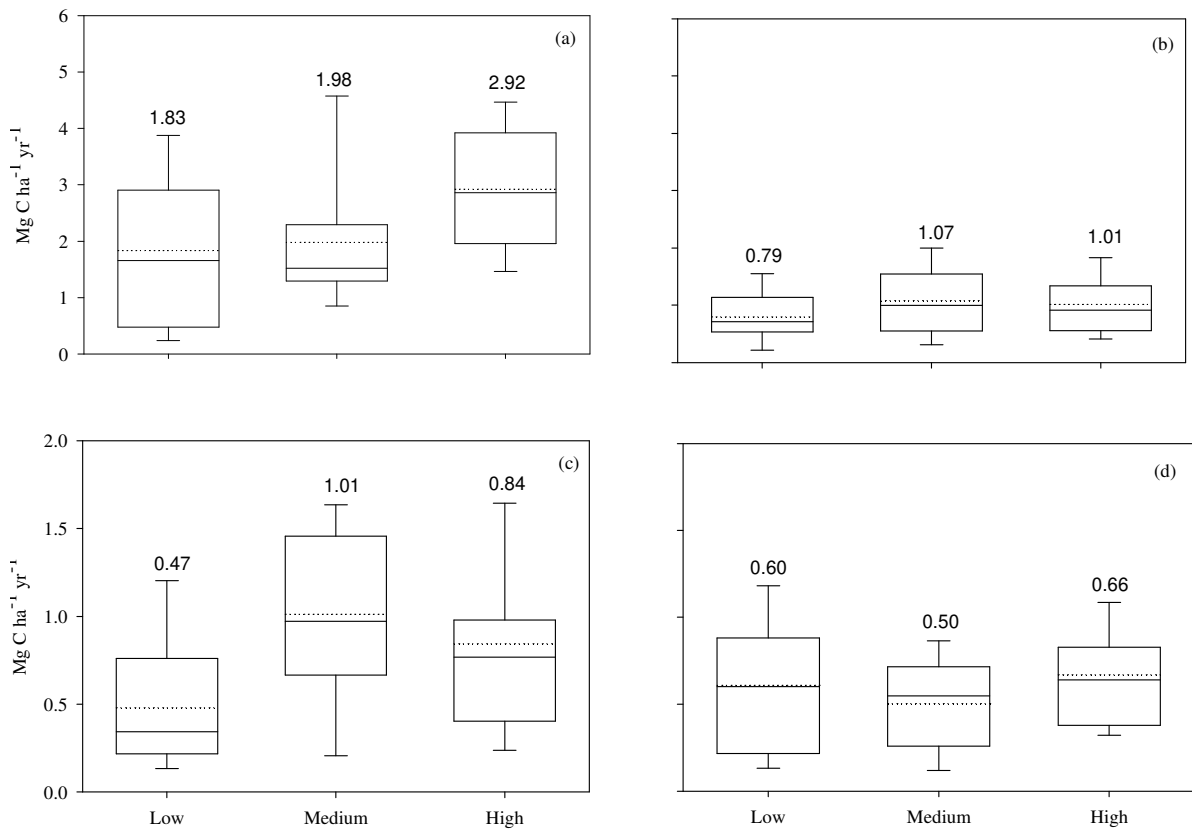
**Fig. 3** Carbon allocation into the soil as a proportion of (a) Pc (b) Sc, (c) Rc, and (d) REc.



**Fig. 4** Respired Carbon allocation into the soil as a proportion of (a) Pc (b) Sc, (c) Rc, and (d) SOc.



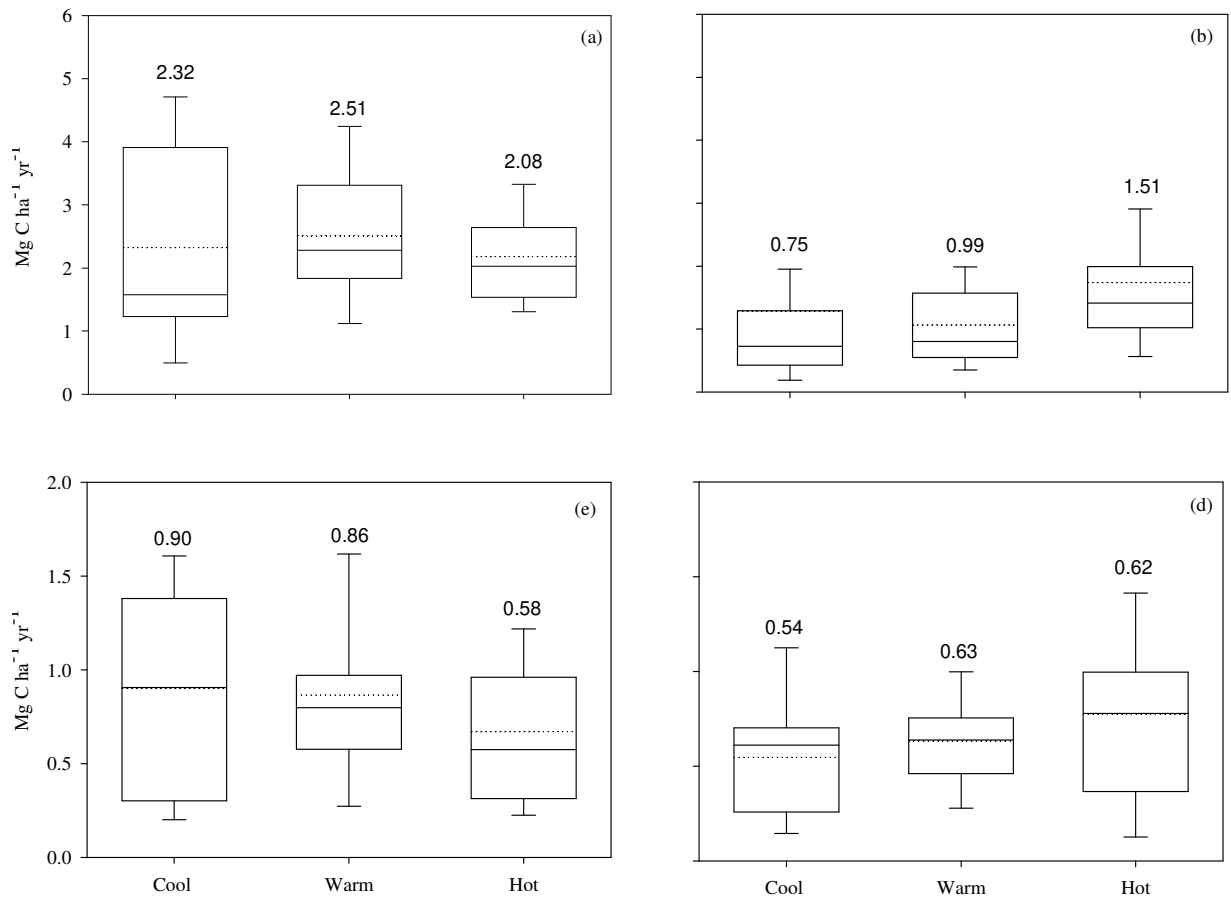
**Fig. 5** Carbon allocation into (a) Sc (b) Rc, (c) REc, and (d) SOc.



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key: Low=<10gCkg<sup>-1</sup>, medium=10-15gCkg<sup>-1</sup> and high= >15gCkg<sup>-1</sup>

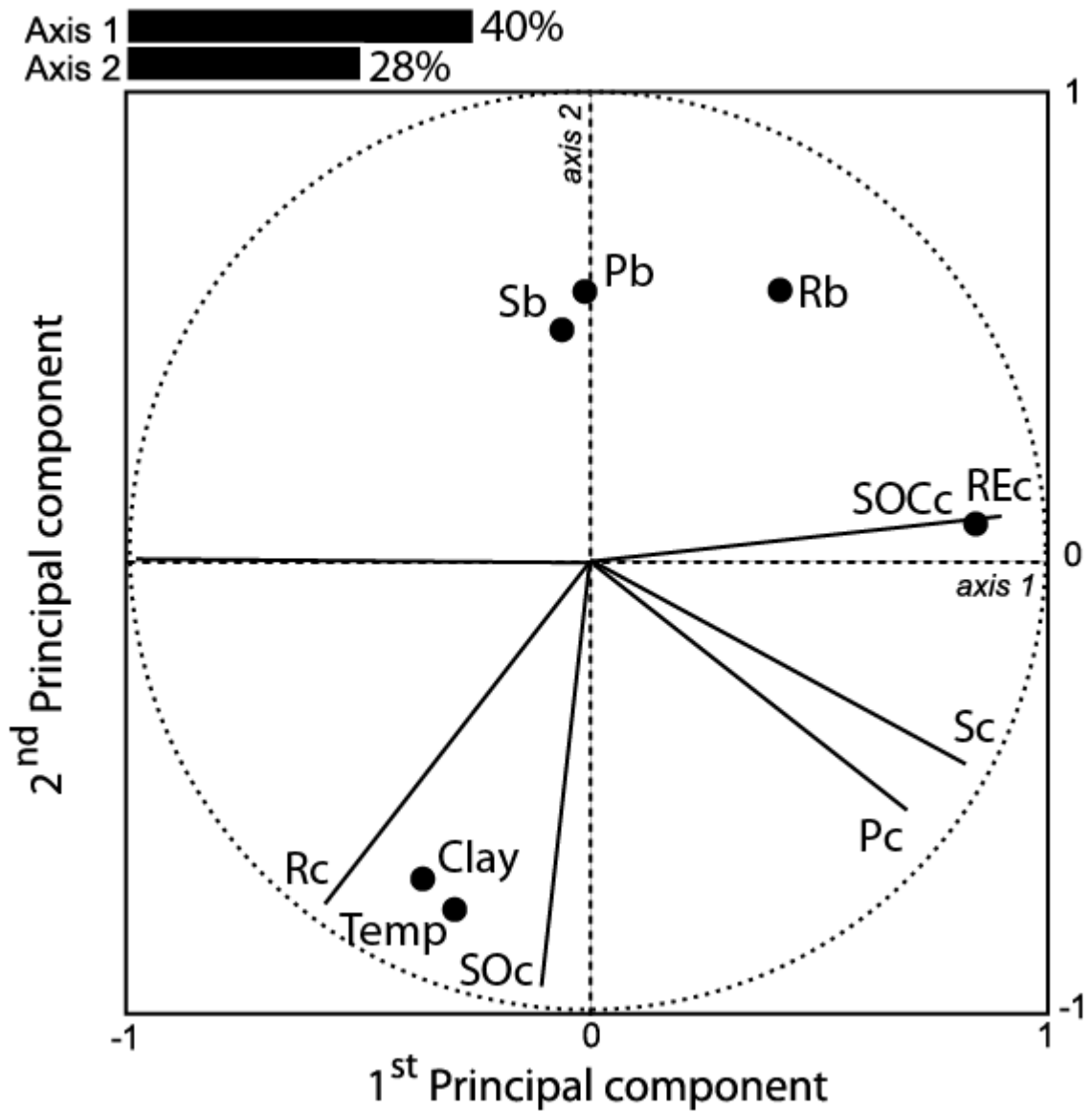
**Fig 6** Impact of soil organic carbon content (SOCc) on carbon allocation into (a) Sc, (b) Rc, (c) SOc, and (d) REc. See table 2 for SOCc classes.



Key: Cool= <10°C, warm= 10-25°C and hot >25°C

**Fig 7** Impact of air temperature on carbon allocation into (a) Sc, (b) Rc, (c) SOc, and (d) REc.

See table 2 for SOc classes.



**Fig 8** PCA showing multivariate relationship among variables and factors all plant types. Sc=shoot C allocation, Rc=root C allocation, SOc=soil C allocation, REc=soil respiration, Rb=root biomass, Pb=plant biomass, Rb/Sb=biomass root:shoot, Temp=temperature and SOCC=soil organic C content. See Table 2 for full description of variables.

**Table 1** List of authors, countries, crop types studied and type of experiment carried out using an identified carbon isotope

No.	Author	Country	Isotope	Crop	Experiment	Soil cm
1	Aljazairi et al. 2015	Spain	13C	Cereal	Greenhouse	
2	An et al. 2015	China	13C	Cereal	Field	0-15
3	Aranjuelo et al. 2009	Spain	12C	Cereal	Greenhouse	
4	Bazot et al. 2006	Switzerland	14C	Grass	Field	NA
5	Butler et al. 2004	USA	13C	Grass	Greenhouse	
6	Chaudhary et al. 2012	USA	13C	Grass	Greenhouse	
7	Davenport and Thomas 1988	Canada	14C	Cereal, grass	Greenhouse	
8	de Graaf et al. 2009	USA	13C	Cereal	Greenhouse	0-25
9	de Neergaard and Gorissen	Denmark	14C	Grass, legume	Greenhouse	
10	Domanski et al. 2001	Germany	14C	Grass	Greenhouse	
11	Fan et al. 2008	China	13C	Cereal, legume	Greenhouse	
12	Fang et al. 2016	Australia	13C	Cereal	Field	0-30
13	Fernández et al. 2003	Spain	14C	Cereal	Greenhouse	
14	Gocke et al. 2011	Germany	14C	Cereal, grass	Field	NA
15	Gregory and Tawell 1991	Australia	14C	Cereal	Field	0-15
16	Harris et al. 1985	USA	14C	Legume	Greenhouse	
17	Hodge and Millard 1998	UK	14C	Cereal	Greenhouse	
18	Hodge et al. 1997	UK	14C	Grass	Greenhouse	
19	Holland et al. 1995	USA	14C	Cereal	Greenhouse	
20	Kaiser et al. 2015	Australia	13C	Cereal	Greenhouse	
21	Kakiuchi and Kobata 2008	Japan	14C	Legume	Greenhouse	
22	Lodhi et al. 2009	Pakistan	14C	Cereal	Greenhouse	
23	Meng et al. 2013	China	13C	Cereal	Greenhouse	
24	Mutegi et al. 2011	Denmark	14C	Legume	Field	0-10;
25	Qiao et al. 2012	China	13C	Legume	Field	NA
26	Schmitt et al. 2013	Germany	14C	Grass	Greenhouse	
27	Schulze and Poschel 2004	Germany	14C	Cereal	Greenhouse	
28	Swinnen et al. 1995	Netherlands	14C	Cereal	Field	0-20
29	Tian et al. 2013	China	14C	Cereal, grass	Greenhouse	
30	Warembourg et al. 2003	France	14C	Legume, cereal	Greenhouse	
31	Werth and Kuzyakov 2006	Germany	14C	Cereal	Lab	
32	Wu et al. 2008	China	13C	Cereal	Greenhouse	
33	Wu et al. 2010	China	13C	Grass	Field	NA

**Table 2** Definition of C allocation variables and controlling factors as used in this paper

Parameter	Units	Definition	Categories	Remarks
Shoot carbon allocation (Sc)	MgCha <sup>-1</sup> yr <sup>-1</sup>	The amount of C allocated to the shoots	Shoot	All crops used in the study
Root carbon allocation (Rc)	MgCha <sup>-1</sup> yr <sup>-1</sup>	The amount of C allocated to the roots	Root	All crops used in the study
Plant C allocation (Pc)	MgCha <sup>-1</sup> yr <sup>-1</sup>	Sum of the shoot and root C allocations	Plant	All crops used in the study
Soil carbon allocation (SOc)	MgCha <sup>-1</sup> yr <sup>-1</sup>	The amount of C allocated to the soil	Soil	All crops used in the study
Respired carbon from soil (REc)	MgCha <sup>-1</sup> yr <sup>-1</sup>	The amount of C being respired from the soil	Soil respiration	All crops used in the study
Crop type		The broad group to which a plant belongs	Cereals	All monocot grain crops
			Legumes	All N fixing plants
			Grasses	All pasture grasses
Shoot biomass (Sb)	Mgha <sup>-1</sup> yr <sup>-1</sup>	The annual total amount of above ground biomass (leaves and stems) excluding grain lint or pods	All	All crops used in the study
Root biomass (Rb)	Mgha <sup>-1</sup> yr <sup>-1</sup>	The annual total amount of biomass found below the soil surface (crown roots, rhizoms and nodules) excluding stems and leaves.	All	All crops used in the study
Plant biomass (Pb)	Mgha <sup>-1</sup> yr <sup>-1</sup>	The sum of root and shoot biomass	All	All crops used in the study
Clay content (Cl%)	%	The clay fraction of the soil	Sand	below 20%
			Loam	between 20-30%
			Clay	above 30%
			Low	below 10 g C kg <sup>-1</sup>
Soil Organic Carbon content (SOCc)	g C kg <sup>-1</sup>	The C content of the soil at the start of the experiment	Medium	between 10 and 15 g C kg <sup>-1</sup>
			High	above 15 g C kg <sup>-1</sup>
			Cool	up to 10°C
Temperature (Temp)	°C	The average temperature during CO <sub>2</sub> enrichment	Warm	between 10 and 20°C
			Hot	above 20°C



**Table 3** Sample size of C allocation variables stratified by different factors

<b>Variable</b>	<b>Description</b>	<b>Sc</b> <b>200</b>	<b>Rc</b> <b>194</b>	<b>REc</b> <b>142</b>	<b>C<sub>seq</sub></b> <b>153</b>	<b>C<sub>seq</sub>/Sc</b> <b>153</b>	<b>C<sub>seq</sub>/Rc</b> <b>153</b>	<b>REc/Sc</b> <b>142</b>	<b>REc/Rc</b> <b>136</b>	<b>C<sub>seq</sub>/Sb</b> <b>138</b>	<b>C<sub>seq</sub>/Rb</b> <b>138</b>
Crop type	Cereal	130	124	95	96	96	96	95	89	96	96
	Grass	47	47	36	36	36	36	36	36	24	24
	Legume	22	22	10	20	20	20	10	10	18	18
	Non-legume	1	1	1	1	1	1	1	1		
Soil texture	Clay	19	19	7	11	11	11	7	7	4	4
	Loam	39	39	23	31	31	31	23	23	31	31
	Sand	14	14	14	14	14	14	14	14	14	14
	Unclassified	128	122	98	97	97	97	98	92	89	89
SOCc (g C kg <sup>-1</sup> )	High	35	35	21	27	27	27	21	21	27	27
	Low	16	16	6	10	10	10	6	6	10	10
	Medium	17	17	4	6	6	6	4	4	6	6
	Unclassified	132	126	111	110	110	110	111	105	95	95
Temperature (°C)	Cool	49	49	37	49	49	49	37	37	38	38
	Hot	36	36	10	20	20	20	10	10	20	20
	Warm	89	83	73	74	74	74	73	67	70	70
	Unclassified	26	26	22	10	10	10	22	22	10	10

Sc=shoot C fluxes; Rc=root C flux; SOC=soil C flux; REc=respiration C flux; SOC:Sc, SOC:Rc, REc/Scs, REc/Rcs, SOC/Sb and SOC/Rb are ratios of the respective variables

Table 4. Summary statistics on plant parameters, C allocation to plant parts and soil parameters based on data collected from field and greenhouse evaluations.

Statistics	Plant parameters								C allocation						Soil parameters			
	Sb		Rb		Pb		Rb/Sb		Sc		Rc		Pc		Clay		SOCc	
	-----Mgha <sup>-1</sup> -----								-----Mgyr <sup>-1</sup> ha <sup>-1</sup> -----						%		gkg <sup>-1</sup>	
	FD	GH	FD	GH	FD	GH	GH	FD	FD	GH	FD	GH	FD	GH	FD	GH	FD	GH
Observations	34	87	34	84	34	87	34	114	81	114	71	129	81	114	36	17	22	45
Mean	124.7	152.2	36.6	16.6	161.30	168.30	0.505	2.545	2.32	2.55	0.97	1.07	4.30	4.63	21.94	20.78	10.89	17.28
Variance	69923	349708	2388	1292	81764	351412	0.17	1.57	1.71	1.57	0.33	0.66	19.95	7.10	80.21	108.66	7.56	59.93
St dev	264.40	591.40	48.86	35.94	285.90	592.80	0.4196	1.2531	1.31	1.25	0.58	0.81	4.47	2.67	8.96	10.42	2.75	7.74
SEM	45.35	63.40	8.38	3.92	49.04	63.55	0.072	0.117	0.15	0.12	0.07	0.07	0.50	0.25	1.49	2.53	0.59	1.15
t value	-0.35		2.16		-0.09		-14.82		-1.21		-1.01		-0.59		0.42		-4.93	
df	116		48		114		144		193		185		120		51		61	
p-value	0.725ns		0.036*		0.93ns		0.001**		0.228ns		0.313ns		0.559ns		0.678ns		0.001**	

\* and \*\* denote significant difference at P<0.05 and p<0.01, respectively; ns=non-significant difference. df=approximate degrees of freedom, FD=field condition, GH=greenhouse condition, SEM=standard error of mean, St dev=standard deviation. Sb=shoot biomass, Rb=root biomass, Pb=total plant biomass, Rb/Sb=root to shoot ratio, Sc=C allocation to shoot, Rc= C allocation to root, Pc= C allocation to plant, SOCc=soil organic carbon content.

In the materials and methods were need to mention that the variation between field and greenhouse data was tested using the independent two-sample t-tests at 95% confidence level using Genstat 18<sup>th</sup> edition. The parameters measured under field conditions were treated as independent samples from the greenhouse data and the two samples were regarded as heteroscedastic samples during the procedure for t-tests (Yang et al 1992).

Yang, S. R., Koo, W. W., & Wilson, W. W. (1992). Heteroskedasticity in crop yield models. Journal of Agricultural and Resource Economics, 103-109.

**Table 5** Spearman rank correlation coefficients showing pair-wise relationship among C flux variables and controlling factors used in the study for all crops

	Temp	Cl%	SOCc	Sb	Rb	Sc	Rc	C <sub>seq</sub>	REc	C <sub>seq</sub> :Sc	C <sub>seq</sub> :Rc	REc/Sc	REc:Rc	C <sub>seq</sub> /Sb	C <sub>seq</sub> /Rb
<b>Variables</b>															
<b>Temp</b>	1.00														
<b>Cl%</b>	0.66*	1.00													
<b>SOCc</b>	0.23*	0.91*	1.00												
<b>Sb</b>	-0.15	-0.79*	-0.66*	1.00											
<b>Rb</b>	-0.03	-0.61*	-0.37*	0.80*	1.00										
<b>Sc</b>	-0.04	-0.11	0.20	0.02	-0.20*	1.00									
<b>Rc</b>	0.04	0.21*	0.44*	-0.12	0.04	-0.01	1.000								
<b>C<sub>seq</sub></b>	-0.01	0.46*	0.11	-0.13	-0.18	0.11	0.38*	1.00							
<b>REc</b>	0.34*	-0.28*	0.20*	0.09	0.09	0.19*	0.33*	-0.12	1.00						
<b>C<sub>seq</sub>:Sc</b>	0.04	0.40*	0.48*	-0.17	-0.05	-0.51*	0.33*	0.75*	0.01	1.00					
<b>C<sub>seq</sub>:Rc</b>	-0.14	0.07	-0.23	-0.04	-0.14	0.22*	-0.67*	0.35*	-0.23*	0.18*	1.00				
<b>REc/Sc</b>	0.11	-0.26	0.49*	0.05	0.12	-0.59*	0.23*	-0.02	0.57*	0.41*	-0.31*	1.00			
<b>REc:Rc</b>	0.02	-0.19	-0.16	0.11	0.24*	0.03	-0.78*	-0.34*	0.25*	-0.31*	0.62*	0.18*	1.00		
<b>C<sub>seq</sub>/Sb</b>	0.01	0.04	0.01	0.10	0.12	0.02	0.03	0.72*	0.13	0.69*	0.58*	0.13	0.05	1.00	
<b>C<sub>seq</sub>/Rb</b>	0.04	-0.35*	-0.10	0.24*	0.22*	0.11	-0.08	0.59*	0.19	0.48*	0.58*	-0.03	0.16	0.88*	1.00

\*=significance at  $p \leq 0.05$

Temp=temperature; Cl%=soil clay content; SOCc=soil organic carbon content; Sb=shoot biomass; Rb=root biomass; Sc=shoot C fluxes; Rc=root C fluxes; Soc=soil C fluxes; REc=respiration C fluxes; SOc:Sc, SOc:Rc, REc/Scs, REc:Rcs, SOc/Sb and SOc/Rb are ratios of the respective variables