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1 **Crop residues differ in their decomposition dynamics: review of available** 2 **data from world literature**

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9 10 **ABSTRACT**

11 Decomposition of crop residues may affect soil organic carbon (C) stocks, which are key for
12 soil fertility improvement and mitigation of climate change. Numerous independent studies
13 across the world point to contradictory results but their existence provides an opportunity to
14 conduct a comprehensive analysis of the impact of crop type on residue decomposition. In the
15 present study, data from 394 trials from across the world were used to assess cumulative
16 CO₂ emissions from residues of 17 crops during 0-30, 0-90 and 0-120 days (i.e. C_{R30}, C_{R90}
17 and C_{R120}; 1-[C_{R30}/C_{R120}] ratio as a stability index of C emissions) and to relate the results
18 with residue quality (C, N and lignin concentrations) and selected soil properties (texture, pH,
19 soil organic carbon concentration). At all durations, legumes exhibited the
20 highest CO₂ emissions per gram of C added (1003 mg CO₂-C g⁻¹C after 120 days) followed
21 by grasses (947), oilseed crops (944) and cereals (846), with the legumes and grasses
22 showing the lowest temporal stability of C emission as pointed out by a 1-[C_{R30}/C_{R120}] of
23 0.78 and 0.79, respectively, versus 0.82 and 0.83 for cereals and oilseed crops. At all
24 durations, maize residues emitted the least C-CO₂ (86, 275 and 495 mg CO₂-C g⁻¹C),
25 followed by two other lignin rich crops (cotton and sunflower), while the highest emissions

26 were from Alfalfa residues that produced about 4 times more CO₂ (e.g. 359 at C_R30 and 1319
27 at C_R120) than maize. Overall, CO₂ emissions were positively correlated with soil clay
28 concentration ($r > 0.22$), residue C concentration (e.g. $r = 0.46$ at C_R90 and $r = 0.37$ with
29 emission stability, $P < 0.05$) but negatively to residue N concentration ($r = -0.26$ at C_R120,
30 $P < 0.05$). The global trend pointed to decreased CO₂ emissions with increasing residue lignin.
31 Contrary to what is generally believed, providing the soil with high lignin and high N
32 concentration may foster C stabilization into soils by soil microbes.

33 *Keywords:* Crop residue decomposition, C emissions, Soil carbon stabilisation, Soil C stocks

34

35 **1. Introduction**

36 The carbon (C) cycle has received considerable attention in recent years, due to concerns
37 over the continued increase in atmospheric carbon dioxide (CO₂) concentration. Annual
38 increases of CO₂ concentration in the atmosphere were observed on a global scale for the
39 years 2018 (2.7%) and 2019 (0.6%) (Ritchie and Roser, 2020). Global warming, as a result of
40 high atmospheric CO₂ causes climate change, characterized by increase in mean temperature
41 and higher variability in precipitation. Consequently, the need to sequester carbon in
42 agricultural soils has been identified as a sustainable strategy to mitigate climate change and
43 promote agricultural sustainability.

44 Soil is the second largest C reservoir with 11% (4655 Pg C), after the 87% of global carbon
45 stocks being oceanic (38,000 Pg C) and has higher C than the 2% found in the atmosphere
46 (860 Pg C) (Xiao, 2015; Venter et al., 2021). Carbon transfer from the atmosphere to soil is
47 achieved by plants through photosynthesis, leading to exudation of C compounds from roots
48 during the growth cycle, and by the retention of plant root and shoot residues. Some of the C
49 from plant residues or exudates can be mineralized and emitted back to the atmosphere as
50 CO₂ while a significant proportion can be stabilized as soil organic matter (Ontl and Schulte,
51 2012; Dignac, 2017). Therefore, the rate of residue decomposition and associated CO₂
52 emissions is often used as a proxy for evaluating the potential of plant residues to become soil
53 organic matter (e.g. Johnson et al., 2007).

54 The potential to increase soil C stocks is mostly on managed agricultural land where
55 numerous studies exist on the fate of C from different crop residues. Curtin et al. (2008) for
56 instance, observed that barley straw emitted significantly higher ($p < 0.05$) amount of CO₂
57 (55 g CO₂-C m⁻²) compared to wheat straw (47 g CO₂-C m⁻²) after 158 days. Ajwa and
58 Tabatabai (1994) found 58% of organic C evolved as CO₂-C from alfalfa-treated soils in 30
59 days which was higher compared to maize residues (30%), which was attributed to the higher

60 C: N of maize residues. Zeng et al. (2010) attributed the higher CO₂ emissions from peanut
61 root (maximum of 60 %) compared to maize root residues (35%) to biological nitrogen
62 fixation, which increases N in leguminous plants, and thus lower their C: N ratio, and overall
63 quality of the crop residues. Not only does crop residue decomposition depend on the type
64 and quality of crop residues but also on the internal soil conditions (Mathew, et al., 2017;
65 Stewart et al., 2015).

66 Mathew et al. (2017) concluded that higher plant C stocks and C transfer to soils occurred in
67 carbon rich clayey soils of tropical humid areas due to higher biomass production potential
68 compared to sandy soils. Clayey soils also support high C stocks through their aggregation
69 and ability to provide physical protection as well as mineral adsorption of C constituents
70 (Elliott, 1986; Ajwa and Tabatabai, 1994; Martens, 2000; Clark, 2007; Mathew, et al., 2017).

71 Several studies have also reported disparities in CO₂ emissions from residues of different
72 crops under different soil types and climates, which has led to a lack of consensus on the
73 impact of these factors on CO₂ emissions from soils (Li et al., 1994; Paustian et al., 2000;
74 Gregorich et al., 2001; Alvarez, 2005; Abdalla et al., 2016; McClelland et al., 2021; Shakoor
75 et al., 2021). However, the existence of multiple individual studies across the world provides
76 an opportunity to conduct a comprehensive analysis of the main factors that control crop
77 residue decomposition and CO₂ emissions and the consequences for the building of soil
78 carbon stocks. Therefore, the objective of the current study was to evaluate the impact of crop
79 type, soil and environmental factors on CO₂ emissions from residues of selected crops using
80 available global data from published studies.

81

82 **2. Materials and methods**

83 *2.1. Study setup: Database preparation*

84 Data on CO₂ emissions from crop residues incubated in soil at laboratories were collated
85 from studies across the world, published in peer reviewed journals and accessible from public
86 domains such as Google scholar, Ref-seek, Science Direct, Sci-Finder, Scopus, Springer
87 Link, Research-Gate and Web of Science. Key words such as “litter decomposition”, “residue
88 decomposition”, “C mineralisation”, “crop residue CO₂ emissions”, “C gases”, “carbon
89 dynamics” and “decomposition rate” were used to search for relevant journal articles. The
90 available papers had to report on CO₂ emissions from crops (sorghum, wheat, maize, among
91 others) and on crop quality factors affecting residue decomposition (e.g. total C and N, C: N
92 ratio, lignin, cellulose or hemicellulose). Furthermore, environmental factors such as climatic
93 information (mean annual precipitation and mean annual temperature), geographic variables
94 (latitude, longitude) as well as soil variables (physicochemical properties) measured during
95 both laboratory or/and field experiments were considered as controlling variables. The studies
96 had to strictly compare CO₂ emissions between soils incubated with and without (considered
97 as the control) residues under the same conditions. Moreover, the mass of residues used must
98 have been clearly stated or able to be deduced. The data were used to compile a database with
99 quantitative and qualitative data on plant litter quality.

100

101 *2.2. Variables of CO₂ emission*

102 The effect of adding crop residues on soil CO₂ emissions were calculated as the difference
103 between CO₂ emitted from the soil containing residues and CO₂ evolved from the control.
104 The values were converted from their original units and normalized to common units (mg
105 CO₂-C/ g C added of soil over 30, 90 and 120 day periods of incubation) (Table 2). The
106 amounts of total CO₂ emissions were recorded over 0-30; 30-90 and 90-120 day periods and
107 were cumulatively representing lability of residue decomposition. The studies that did not
108 cover the 0-30, 30-90 and 90-120 periods were estimated by use of linear trendline equation.

109 In addition, a ratio between CO₂ emissions at 30 relative to 120 days was calculated, which
110 was used as an index of temporal stability of C-CO₂ emissions = 1- (C_{R30}/ C_{R120}). The
111 greater the index, the greater stability of the emissions over time.

112

113 *2.3. Crop quality, soil and environmental factors*

114 Crops were categorized into cereals, legumes, grasses and oilseed (Table 3), (i.e., cereals-
115 barley, maize, oat, rice, rye, sorghum, wheat; grass- grass; legumes-alfalfa, bean, clover, pea,
116 soyabean, vetch; and oilseed-canola, cotton, and sunflower). Cereals and grasses were
117 separated due to their functional differences, with cereals having evolved and undergone
118 selection by farmers, making them different from natural or forage grasses. In this study,
119 grasses refer to natural or forage grass that are not used for human consumption while cereal
120 refers to monocot grasses that are used primarily for grain production for human
121 consumption. Legumes are defined as any crop that has a natural ability to fix nitrogen, while
122 oilseed crops are those that are primarily used for extraction of vegetable oil from their seed.
123 Soyabean was considered as a legume crop in this study. Furthermore, crop quality was
124 defined by residue chemical composition, such as initial C (TC) and lignin concentrations,
125 C:N ratio, total nitrogen (TN), dissolved carbon (DC) and total phosphorus (TP); cellulose,
126 polyphenols and lignin: N ratios. In addition, soil properties such as texture (clay, silt and
127 sand concentration), soil pH (CaCl₂) and organic carbon (SOC) were considered and
128 classified into different categories (Table 3) following Abdalla et al. (2016); Mutema et al.
129 (2015) and Mathew et al. (2017). Water-based pH was converted to CaCl₂ pH following the
130 equation of Lierop (1981): ($y = 0.53 + 0.98x$). Where y is pH on the CaCl₂ scale and x is the
131 water-based pH.

132 Climatic factors included a 30-year average rainfall and temperature (mean annual
133 precipitation: MAP) and (mean annual temperature: MAT). The climate was further classified

134 as tropical (hot and wet), sub-tropical (warm and arid to humid) or temperate (cool to cold
135 and mild to warm). In cases where climatic characteristics were not present in a particular
136 study, appropriate data such as annual precipitation and temperature were obtained using the
137 location coordinates or surrogate data for nearby prominent features (e.g. town) through
138 Google search. In addition, the geographical positioning system (GPS) using latitude and
139 longitude coordinates were used to depict the global distribution of the studies used in the
140 review (Fig. 1).

141 A total of 58 journal articles (Table 1) were used, detailing different studies across the world,
142 which provided 394 observations. The name of authors, year of paper publication, country
143 and geographical location of experimental site, nature of experiment, experimental duration
144 (time periods), crop(s) or crop types used in the experiments, quantitative information on
145 plant quality, soil properties as well as C variables and environmental conditions were
146 captured onto a database. The definitions and acronyms adopted in this paper are used to
147 simplify the terms and definitions of variables for purposes of this analysis.

148

149 *2.4. Data analyses*

150 The data were compiled into a database and tested for normality of variables, linearity and
151 homoscedasticity prior to statistical analyses. Descriptive summary statistics (minimum,
152 maximum, median, mean, SEM: standard error of mean, 25th and 75th percentiles, skewness
153 (Skew), kurtosis (Kurt) and coefficient of variation (CV%) were calculated for all variables
154 (Table 6). Furthermore, box plots were constructed to depict the distribution of the data
155 showing minimum, 25th quartile median, mean, 75th quartile and maximum values within the
156 5 and 95th percentiles. Mean CO₂ emissions were computed for different crops, with different
157 crop residue quality, soil properties and environmental factor classes. Because the CO₂
158 emission data did not conform to normal distributions for us to use parametric analysis, the
159 non-parametric Kruskal-Wallis analysis was performed. Significant differences between
160 factor classes were tested with non-parametric analysis (Kruskal-Wallis), at chi-square
161 probability of <0.001. In addition, bivariate Pearson correlations coefficients at p<0.05 were
162 calculated among the variables (Table 7). Subsequently, principal component analysis (PCA),
163 which converts non-linear factors and variables into linear combinations for visualization
164 (Jambu, 1991), were conducted to investigate the multiple correlations between the variables
165 (Fig. 10 and 11). Finally, because of low number of data points the variable of residue
166 dissolved carbon, total residue phosphorus, cellulose and polyphenols were discarded. SiAll
167 analyses were performed using Statistica 10.0 software (Weiß, 2007).

168

169 **3. Results**

170 *3.1. CO₂ emissions from crop residues*

171 The summary statistics (Table 4) which were computed from all study sites showed that the
172 30-days cumulative CO₂ emissions (C_{R30}) ranged between 0.3 and 920.1 mg CO₂-C g⁻¹ C,

173 with a mean value at 196.5 mg CO₂-C g⁻¹ C. Cumulative 120 days emissions (C_R120) were
174 between 3.2 and 3640 mg CO₂-C g⁻¹ C with a mean at 914.2 mg CO₂-C g⁻¹ C (Table 4). The
175 resulting emission stability index showed a mean at 0.8.

176 Cumulative emissions also varied among different crops, with legumes exhibiting the highest
177 mean cumulative emissions of 228.0 mg CO₂-C g⁻¹ C after 30 days, 586.7 mg CO₂-C g⁻¹ C
178 after 90 days and 1003.0 mg CO₂-C g⁻¹ C after 120 days (Table 5). Grasses ranked second
179 with respectively, 217.0, 529.7 and 946.8 mg CO₂-C g⁻¹ C, while oilseed crops ranked third
180 and cereals fourth (Table 5). The average difference between legumes and cereals was 25%
181 after 30 days, 19% after 90 days and 16% after 120 days, which corresponded for C_R30 and
182 C_R90 to significant differences at P<0.001. On average, legumes had the lowest temporal C
183 emissions stability (0.78) followed by grass (0.79), cereals (0.82) and oilseed (0.83)
184 (Table 5).

185 Table 6 shows variations in CO₂ emissions between different crop types, with alfalfa having
186 the highest emissions of 359.0 mg CO₂-C g⁻¹C, amongst legumes (48% higher than clover
187 and pea), while canola (293.5) had the highest amongst oilseed crops, and sorghum (261.1)
188 had the highest amongst cereals (67% more than maize) at C_R30. Maize emitted the least
189 cumulative CO₂ at C_R30 (85.8 mg CO₂-C g⁻¹C), C_R90 (275.1) and C_R120 (495.0) but
190 exhibited with 0.84 the highest CO₂ emission stability over time. In contrast, alfalfa exhibited
191 the lowest stability of CO₂ emissions with a mean value at 0.76, followed by rye (0.77),
192 clover and pea (0.78), canola, grass and oat (0.79) (Table 6; Fig. 2D).

193 3.2. *The influence of crop residue quality on CO₂ emissions*

194 The quality of crop residues, determined by the initial C, N and lignin concentrations,
195 significantly ($p < 0.05$) affected CO₂ emissions (Table 7). There was a systematic decrease in
196 C emissions with the increase in residue nitrogen content with r from -0.22 at C_{R30}, -0.26 at
197 C_{R120} and -0.28 at C_{R90}. The r values with lignin content were from -0.08 at C_{R30} to -0.12 at
198 C_{R120}. Emissions also decreased with increasing C:N with the highest r (-0.14) found for
199 C_{R30}. In contrast C emissions increased with increasing residue C content from 0.40 at
200 C_{R120} to 0.59 at C_{R30}. Furthermore, the increase in residue C content significantly enhanced
201 the temporal stability of C emissions ($r = 0.37$).

203 3.3. *The impact of soil and environmental properties on CO₂ emissions from different* 204 *crop residues*

205 There were significant variations in cumulative CO₂ emissions among the three different soil
206 textural classes throughout the incubation periods (Fig. 4). For instance, clayey soils
207 exhibited significantly higher cumulative 30-days CO₂ emissions (224 mg CO₂-C g⁻¹ C) as
208 compared to sandy soils (178 mg CO₂-C g⁻¹ C), while silty soils had intermediate emissions.
209 Decreasing emissions with increasing sand content was a trend also found for C_{R90} and
210 C_{R120}. Finally, the temporal stability of CO₂ emissions was surprisingly the highest under
211 silty conditions ($1 - (C_{R30}/C_{R120}) = 0.81$) and decrease to 0.80 under clayey conditions and to
212 0.79 for sandy soils (Fig. 4).

213 Cumulative CO₂ emissions also varied due to soil pH (Fig. 5). For all incubation durations,
214 the lowest emissions were observed for strongly acidic soils while the highest emissions were
215 found for slightly acidic soils. Additionally, there was a trend for emissions to lessen from
216 slightly acidic to alkaline through neutral while the temporal stability of the emissions
217 consistently rose from acidic to alkaline (Fig. 5D).

218 Figure 6 which depicts the impact of climate points to a significant decrease of emissions
219 from tropical to temperate through sub-tropical. In the case of C_{R30} , CO_2 emissions
220 decreased from an average of 252 mg $CO_2-C\ g^{-1}\ C$ for tropical to 193 mg $CO_2-C\ g^{-1}\ C$ for
221 subtropical and to 150 mg $CO_2-C\ g^{-1}\ C$ for temperate, which corresponded in all cases to
222 significant differences at $P < 0.01$ (Fig. 6A). Similar trends (i.e. a decrease of emissions from
223 tropical to temperate) were also observed for C_{R90} and C_{R120} but the temporal stability of
224 the emissions consistently rose from tropical to temperate, the differences between sub-
225 tropical and temperate being however non-significant (Fig. 6D).

226 Multivariate correlations between CO_2 emission variables on the one hand and soil and crop
227 residue variables on the other hand are displayed on Figure 7. The two principal components
228 of this PCA explained 99% of the total variation in the data with the first principal component
229 (PC1) accounting for 79% of data variance and PC2 accounting for 20%. Cumulative
230 emissions to 30, 90 and 120 days showed a positive correlation to PC1 and this axis can be
231 thus interpreted as an axis of crop residue decomposition. The temporal stability of CO_2
232 emissions had a negative coordinate on Axis 2, meaning that PC2 could be interpreted as an
233 axis of decomposition in-stability. Residue content in lignin, N and C showed negative
234 coordinates on PC1 while the C:N ratio showed a positive coordinate. There was thus a
235 tendency for emissions to increase as C:N increases but C, N and lignin concentration
236 decreases. Finally, emission instability decreased with increasing pH as pointed by a negative
237 coordinate of pH on PC2 (Fig. 7). Amongst crops, canola and alfalfa correlated to the high
238 CO_2 emissions level and low CO_2 emission stability pole, while maize, cotton and sunflower
239 correlated to the low emissions and high stability pole.

240

241 **4. Discussion**

242 *4.1. Causes of variation in residue decomposition and soil C building amongst crop types*

243 The different crop types exhibited large variations in CO₂ emissions with legumes emitting
244 the highest cumulative CO₂ emissions and with decreasing emissions over time versus cereals
245 pointing to lower emissions but of higher stability. Such variations were shown to correlate
246 with the quality of crop residues (Machinet, et al., 2009). Ajwa and Tabatabai (1994)
247 revealed that the significantly higher amounts of CO₂-C released from alfalfa were to be
248 attributed to their ability to fix N, as they had higher initial N concentration, of 12.6% as
249 compared to the 6.9% of maize and the 1.3% of oilseed crops. The underlying hypothesis of
250 greater emissions at high initial N concentration was, as suggested by Gezahegn, et al.,
251 (2016), the enhanced microbial activity leading to high decomposition and CO₂ emissions.
252 But the present study, which was based on 394 trials from across the world, tends to
253 contradict this past statement as it pointed to a negative correlation between CO₂ emissions
254 and residue N concentration. Such a trend might be due to the fact that N availability
255 enhances C uptake by microbes and thus humus formation versus C emissions to the
256 atmosphere as CO₂, a mechanism that was described by authors such as Henriksen and
257 Breland (1999), Rousk and Bååth (2007), Bai et al. (2016) and Köbke et al. (2018). The fact
258 that legumes, especially Alfalfa which accounted for the most emissions amongst crops
259 during the maximum 120 days period, emitted large amounts of CO₂ despite a high N
260 concentration was most likely due to its low lignin concentration.

261 Carbon stabilization into soils in microbial biomass thus seems to be favoured by the supply
262 of residues with a C and N stoichiometric ratio close to that of living microorganisms. Results
263 on maize, sunflower and cotton tend to show that lignin rich residues experience low
264 decomposition rates which constitutes a second route of carbon stabilization into soils.

265

266 *4.2.The impact of crop residues on the loss of soil carbon through priming*

267 Recent studies have indeed shown that the activity of decomposers and their ability to
268 decompose soil organic matter for their living can be stimulated by the addition of fresh
269 organic matter resulting in an increase in soil respiration beyond C addition, which is referred
270 to as 'priming' (e.g. Fontaine et al. 2003; Kuzyakov, 2010). In the present study and as
271 pointed out in Table 8, 43% of the respiration data points showed 120 days cumulative
272 emissions beyond C addition, which points to the existence of significant C losses from soil
273 organic matter. All crop types experienced priming with the proportion of studies with C
274 losses over residue C from 25% for maize, sunflower and beans to over 55% for sorghum,
275 alfalfa and canola and with differences between legumes, cereals and oilseed crops being
276 non-significant at $p < 0.05$.

277 Several authors have suggested that chemically recalcitrant residues, such as those rich in
278 lignin decompose more slowly than residues with low lignin and high N concentrations, thus
279 leading to enhanced C stabilization into soils and increased soil organic matter (Johnson et al.
280 2007, Berg and Mc Clagherty, 2008). However, several other authors such as Stewart et al.
281 (2015), pointed out that high lignin residues are used inefficiently by the soil microbial
282 community that decompose SOM (priming effect) to acquire key nutrients resulting in much
283 greater respiration losses and less C stabilization into soils. The present study which points to
284 a global tendency for CO₂ emissions to decrease with the increase in residue lignin and N
285 concentration tend to show that providing the soil with high lignin and high N concentration
286 may limit priming and foster C stabilization into soils by soil microbes. Moreover, the present
287 data showed that lignin concentration minimally impacted the temporal stability of the
288 emissions but that emissions decreased more sharply over time at higher initial residue C
289 concentration.

290

291 *4.3. The impact of soil properties on CO₂ emissions*

292 Soil texture and pH had significant impact on cumulative CO₂ emissions from crop residues.
293 The higher cumulative CO₂ emissions from clayey soils could be due to favorable living
294 conditions for decomposers than under coarser soil conditions. Moreover, Schmatz, et al.,
295 (2017) also found higher C emissions from clay soils as compared to sandy-loam soils due to
296 high organic carbon concentration in clayey soils and enhanced water retention capability,
297 thus favoring the activity of microorganisms responsible for residue break-down. Contrarily,
298 most previous studies generally had described clay soils to enhance the physical protection
299 and mineral adsorption of C constituents, which was not confirmed by the present analysis of
300 world data from 120 days duration in which clay soils experiences higher CO₂ emissions per
301 gram of residue C added. Addition of labile organic materials (crop residues) to clayey soils,
302 with higher organic carbon, could result in more CO₂ emissions (priming effect) than from
303 sandy loam soils. In addition, such an increase in CO₂ emissions with the increase in soil clay
304 concentration might come as suggested above from higher soil moisture and bacteria
305 concentration, favoring the rapid turnover of residue C.

306 We had no explanation for slightly acidic soils (pH of 5.5-6.4) to experience consistently
307 higher CO₂ emissions (>50%) than the other pH levels irrespective of incubation durations as
308 conditions for fungi and bacteria are not optimal (Hågvar, 1994; Stott and Martin, 1989). A
309 possible reason for the higher CO₂ emissions could be the liming effect of residues that foster
310 the priming of soil organic matter (Wang et al. 2017; Yaowu et al. 2016).

311

312 *4.4. Climate impact on CO₂ emissions*

313 The finding of this study pointed to higher residue CO₂ emissions under tropical conditions
314 than under the other climates throughout the incubation days. Tropical climates tend to
315 experience high temperature and rainfall conditions that are conducive for production of high
316 plant biomass and microbial activity for decomposition. On the other hand, soils of sub-

317 tropical or temperate climates have lower rainfall and cooler temperature thus limiting
318 microbial activity and the biochemical processes involved in residue decomposition (Ontl and
319 Schulte, 2012). As the data used in the present study come from laboratory experiments with
320 controlled conditions of temperature and humidity, the higher decomposition rates and
321 cumulative CO₂ emissions under tropical climates could be due to favourable conditions for
322 microbial activity.

323

324 **5. Conclusions**

325 The analysis of 394 laboratory trials worldwide revealed that on average, legumes exhibited
326 significantly higher CO₂ emissions than cereals, oilseed and fiber crops, with for instance
327 alfalfa emitting 2.7 times more CO₂ after 120 days than maize (Figure 2, Table 6).
328 Additionally, legumes (especially alfalfa) showed the lowest stability of CO₂ emissions over
329 time (i.e., the highest decrease from 30 to 120 days) followed by grasses, cereals and oilseed
330 crops.

331 Amongst the two models for enhanced C sequestration into soils the present analysis points to
332 a global tendency for CO₂ emissions to decrease with the increase in residue lignin. This
333 contrasted with the studies showing that high lignin concentration induce enhanced microbial
334 decomposition and thus C outputs from soils i.e., alfalfa (low lignin and high N
335 concentration) versus maize residue (high lignin and low N concentration). Providing soils
336 with residues with high lignin such as through maize residues may improve C uptake by
337 microbes (a key process in humus formation).

338 A large proportion of the variance in the data remained however unexplained thus calling for
339 further analysis of variables such as soil nutrients, microbial communities and quality of
340 lignin, and of other organic matter compounds. More work is also to be done on selecting
341 crop cultivars for generating superior ones in our fight against land and climate degradation.
342 Finally, the question whether the carbon remaining into the soil after 120 days of incubation
343 will be stabilized to contribute to soil carbon stocks calls for further research to understand
344 the fate and underlying mechanisms of C sequestration into soils.

345

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352

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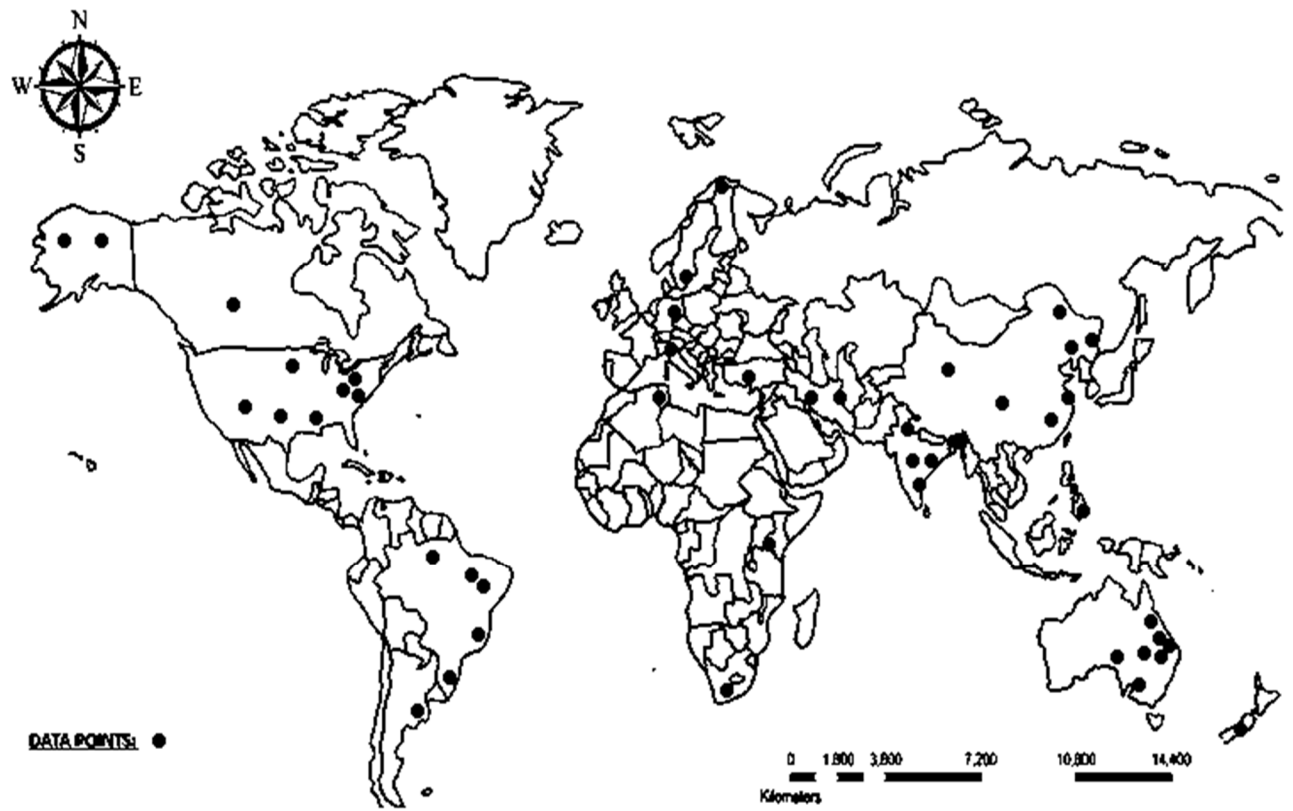
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1
2 **Figure 1:** Global distribution map of the study sites used in the present study.

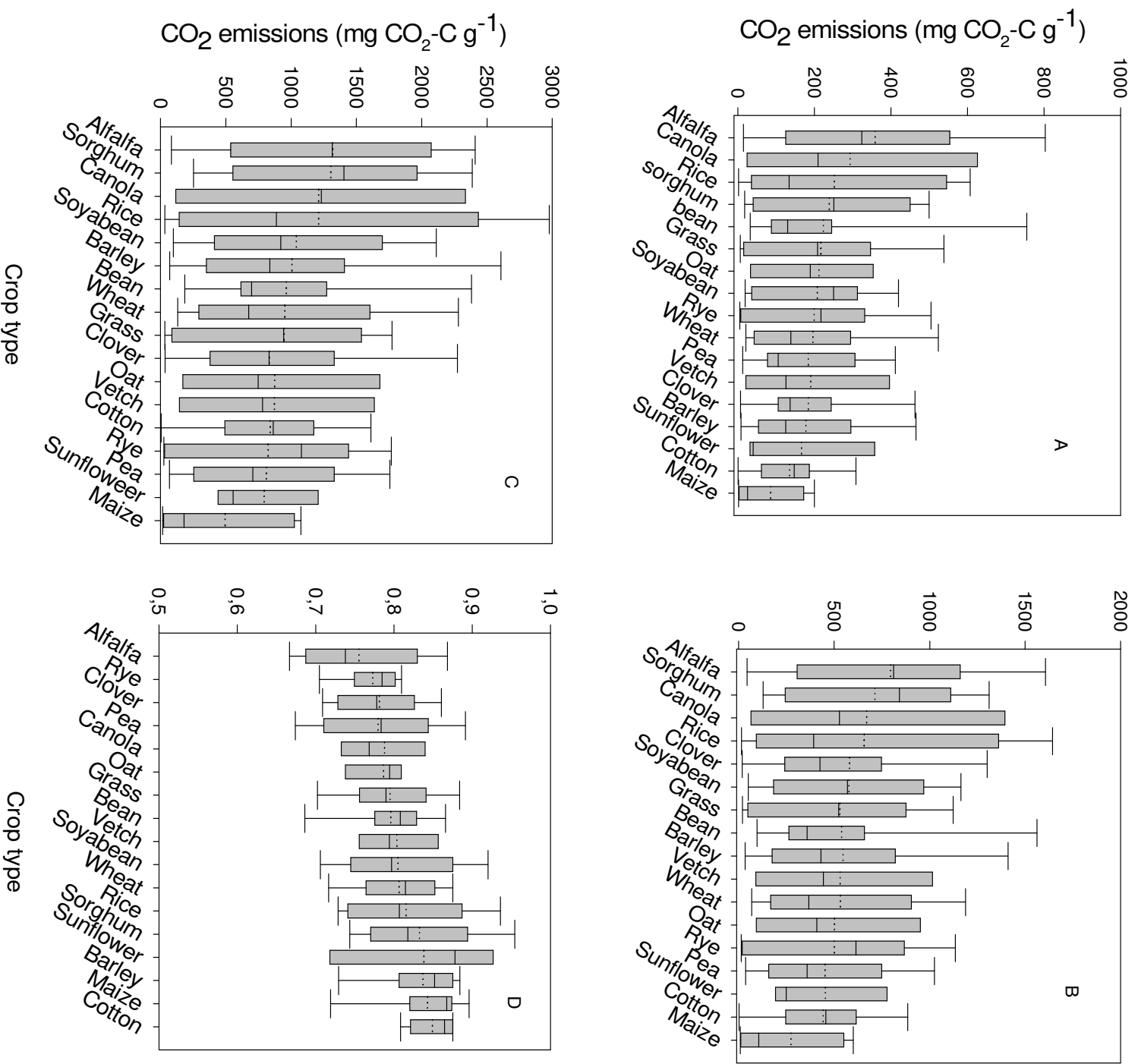


Figure 2: CO₂ emissions from residues of different crops incubated at different time periods (A: cumulative CO₂ emitted from crop residues to 30 days, Cr30; B: to 90 days, Cr90; C: to 120 days, Cr120; and D: 1-[Cr30/Cr120]). The data were sorted by mean (dotted line).

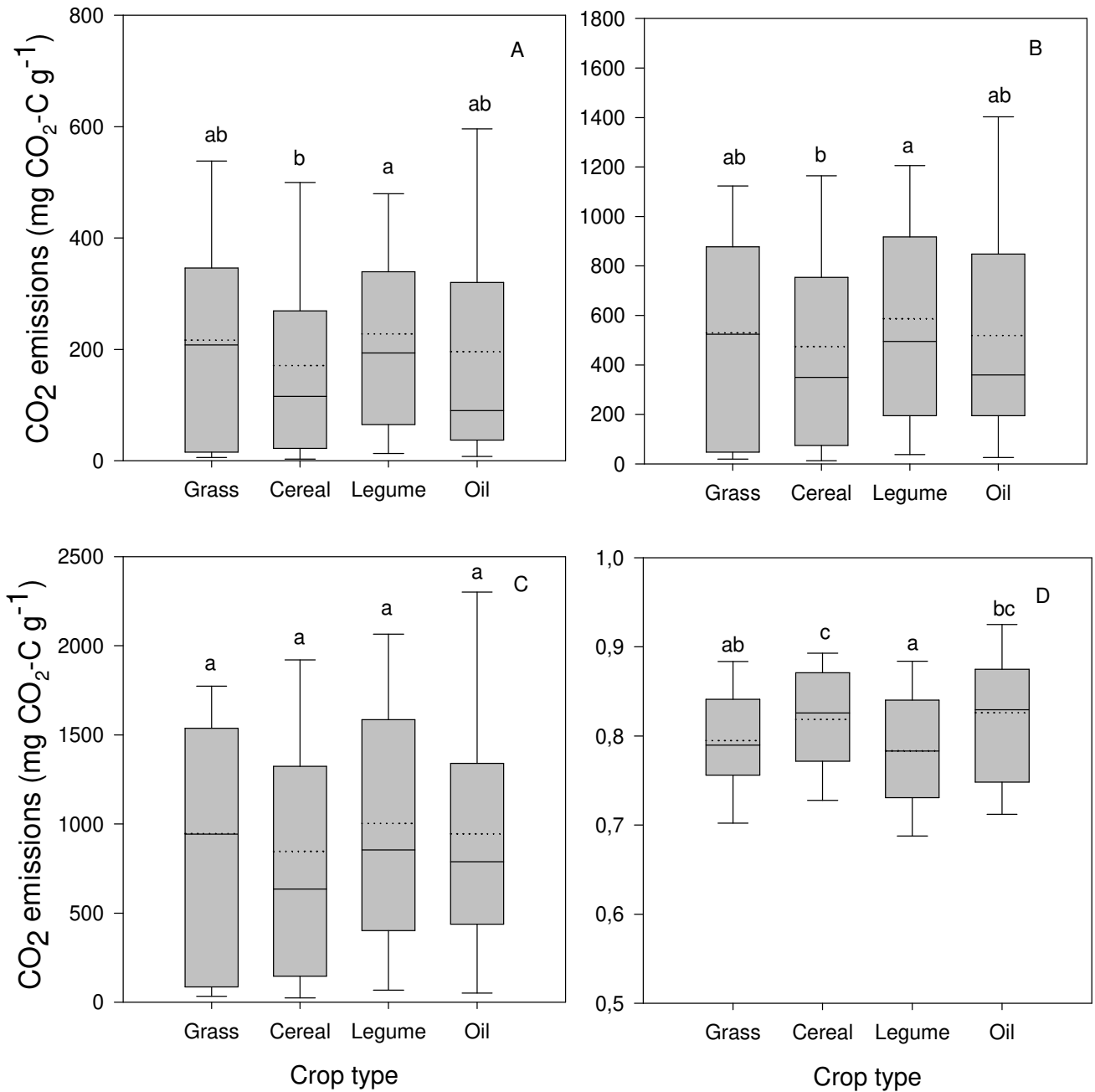


Figure 3: CO₂ emissions from residues of different crop types incubated at different time periods (A: C_R30; B: C_R90; C: C_R120; and D: 1-C_R30/C_R120). Plots with the same lower-case letters are not significantly different at Chi-square probability of < 0.001 (Chi and H values= 0.16. 5.24 at A; 0.08. 6.72 at B; 0.00. 13.79 at C and 0.00. 21005 at D. respectively).

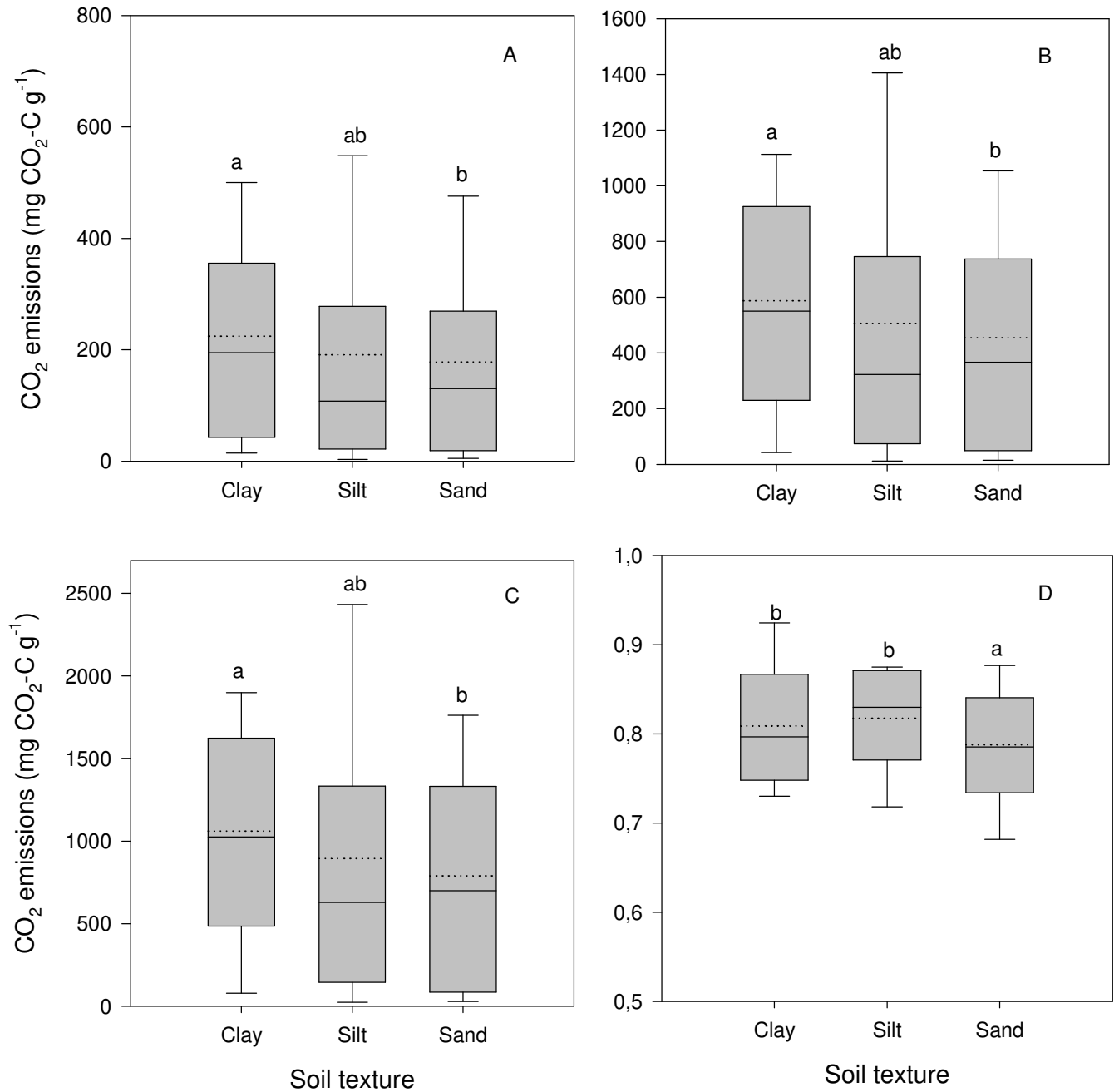


Figure 4: CO₂ emissions from soils of different texture ((%) -clayey, silt and sandy soil) at different day time periods. Plots with the same lower-case letters are not significantly different at Chi-square probability of < 0.001 (Chi and H values= 0.26, 2.67 at A; 0.63, 0.92 at B; 0.10, 4.70 at C; and 0.00, 14.07 at D, respectively).

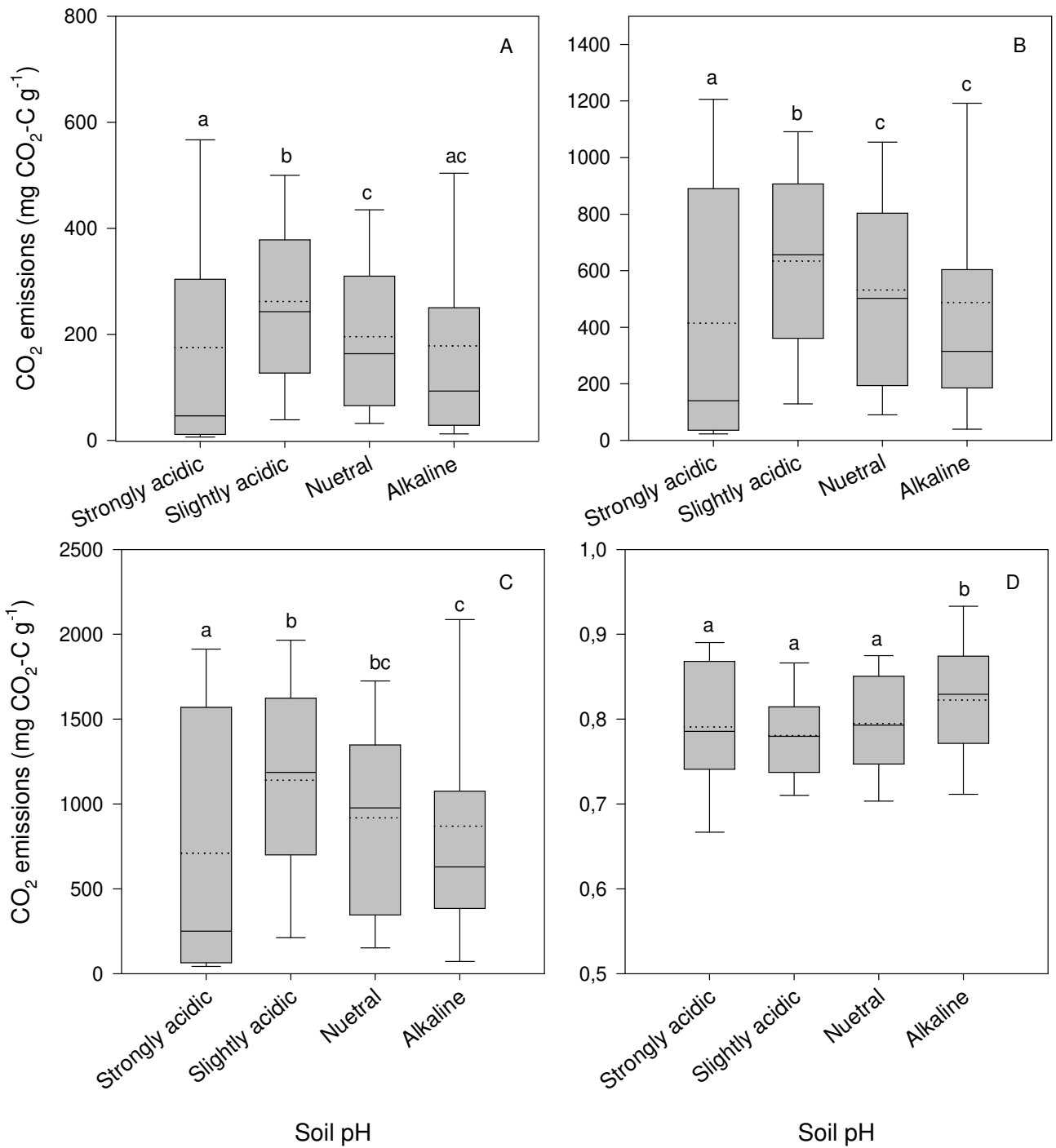


Figure 5: CO₂ emissions from soils of different pH (highly basic. neutral. slightly acidic and highly acidic) at different day time periods. Strongly acidic (pH<5.4); slightly acidic (5.5-6.4); neutral (6.5-7.4); alkaline (>7.5) soil pH. Plots with the same lower-case letters are not significantly different at Chi-square probability of < 0.001 (Chi and H values= 0.01, 10.99 at A; 0.01, 12.64 at B, 0.25, 4.09 at C, and 0.00, 20.92 at D, respectively).

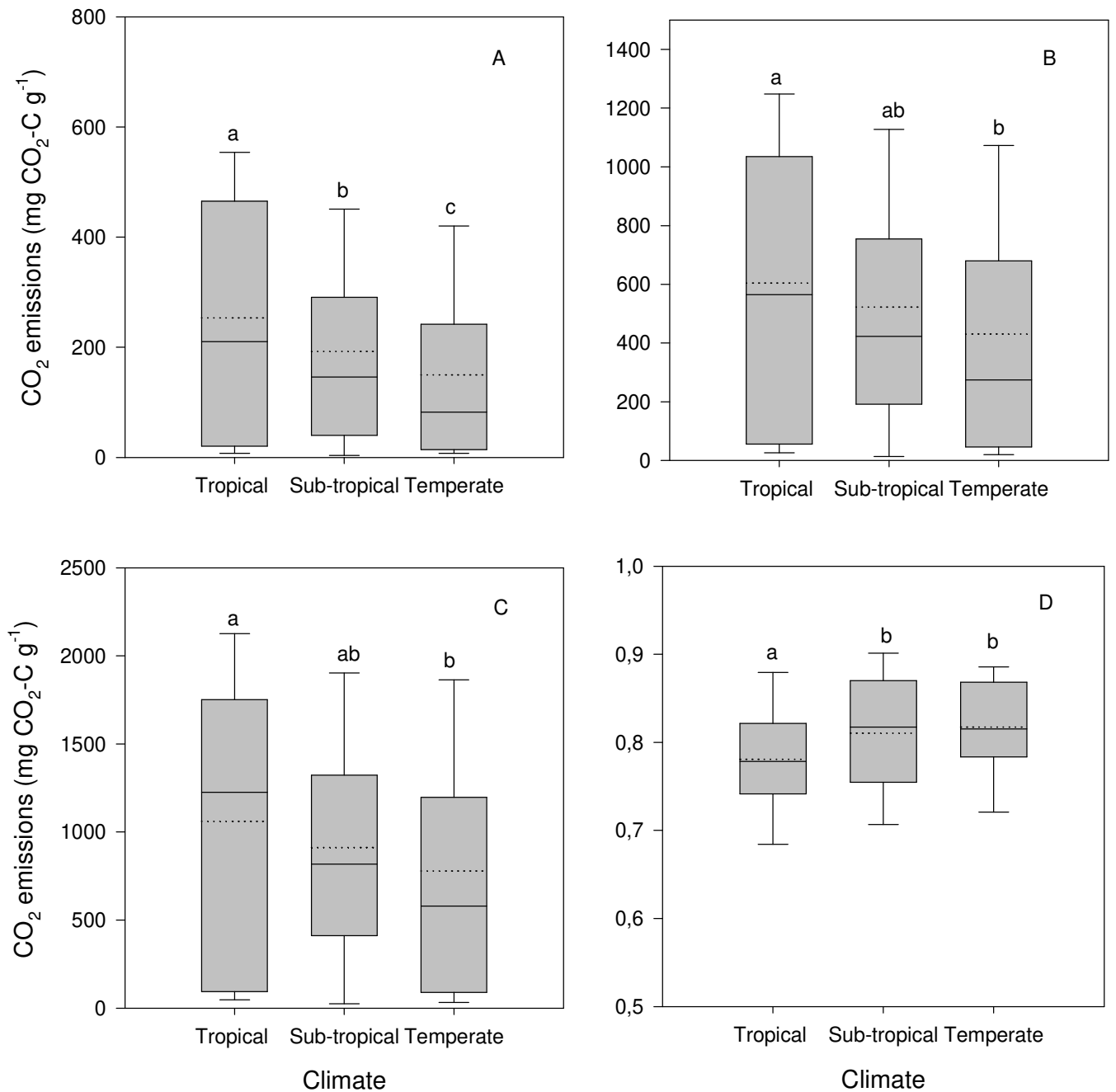


Figure 6: CO₂ emissions from climate of different rainfall and temperature level (as in tropical, sub-tropical and temperate (MAT, MAP) at different day time periods. Plots with the same lower-case letters are not significantly different at Chi-square probability of < 0.001 (Chi and H values= 0.84, 0.34 at A; 0.11, 4.40 at B; 0.68, 0.77 at C, and 0.00, 18.13 at D, respectively).

1 **Table 1:** References included in database with author, country, crops type, soil texture and
 2 climatic zones under which the studies were conducted.

No.	Author	Country	Crop type	Soil texture	Climate
1	Abiven et al. (2005)	Brazil	Brachiaria; Rice; Sorghum; Soyabean; Wheat	Clayey	Tropical
2	Abiven and Recous (2007)	Brazil	Brachiaria; Rice; Sorghum; Soyabean; Wheat	Clayey	Tropical
3	Abro et al. (2011)	China	Maize	Clayey	Subtropical
4	Ajwa and Tabatabai (1994)	USA	Alfalfa; Maize; Sorghum; Soyabean	Silt	Subtropical
5	Angers and Recous (1997)	France	Rye; Wheat	Silt	Temperate
6	Anguria et al. (2017)	Uganda	Cowpea; groundnut; millet; sorghum	(blank)	Subtropical
7	Arunachalam et al. (2003)	India	Bean and pea	Sandy	Tropical
8	Aulakh et al. (1991)	USA	Vetch and wheat	Silt	Tropical
9	Begum et al. (2014)	Australia	Canola; Sorghum; Soyabean; Wheat	Clayey	Subtropical
10	Bertrand, et al. (2006)	France	Wheat	Silt	Subtropical
11	Blaise & Bhaskar (2003)	India	Cotton	clayey,	Subtropical
12	Cayuela et al. (2009)	Italy	Cotton; wheat	Sandy	Subtropical
13	Clark et al. (2007)	Australia	Alfalfa; Wheat	Clayey	Subtropical
14	Cong et al. (2015)	China	Bean; Maize; Wheat	Sandy	Temperate
15	Corbeels et al. (2000)	Morocco	Sunflower; Wheat	Clayey	Temperate
16	Curtin et al. (2008)	New Zealand	Barley; Wheat	Silt	Subtropical
17	Datta et al. (2019)	India	Maize; Rice; Wheat	Silt	Subtropical
18	De Neergaard et al. (2002)	Denmark	Clover; Grass	Silt	Temperate
19	Duong et al. (2009)	Australia	Wheat	Sandy	Subtropical
20	Finn et al. (2015)	Australia	Alfalfa; Grass; Wheat	clayey, Silt& sandy	Subtropical
21	Fruit et al. (1999)	France	Wheat	Silt	Subtropical
22	Gezahegn et al. (2016)	Malaysia	Maize; Soyabean	Sandy	Subtropical
23	Ghimire et al. (2017)	USA	Canola; Oat; Pea	Clayey	Subtropical
24	Havstad et al. (2010)	Norway	Barley; Clover; Grass; Meadow; Wheat	Silt	Subtropical
25	Henriksen and Breland (2002)	Norway	Barley; Clover; Wheat	Silt, sandy	Temperate
26	Jha et al. (2012)	India	Wheat	Clayey	Subtropical
27	Jin et al. (2008)	China	Peanut; Wheat	Silt	Tropical
28	Johnson et al. (2017)	USA	Alfalfa; Cuphea; Maize; Soyabean; Switchgrass	Silt	Subtropical
29	Juan et al. (2009)	China	Rice; Wheat	(blank)	Subtropical
30	Khalil et al. (2005)	Bangladesh	Bean; wheat	clayey, Silt &sandy	Tropical
31	Li et al. (2013)	China	Maize; Soyabean	Silt	Temperate
32	Lou et al. (2007)	China	Rice	Clayey	Tropical
33	Luxhoi et al. (2002)	Denmark	Clover; Grass; Rye	Sandy	Tropical
34	Machinet et al. (2009)	France	Maize	Silt	Temperate
35	Machinet et al. (2011)	France	Maize	Clayey	Temperate
36	Magid et al. (2004)	Denmark	Clover; Radish; Rye; Sugarcane; Vetch	Sandy	Temperate
37	Marstorp and kirchmann (1991)	Sweden	Clover	Sandy	Temperate
38	Martens (2000)	USA	Alfalfa; Canola; Maize; Oat; Prairie	Sandy	Subtropical
39	Moreno-Cornejo et al. (2014)	Spain	Pepper	Silt	Subtropical
40	Muhammad et al. (2011)	Australia	Cotton; Maize; Sorghum, Sugarcane	Clayey	Subtropical
41	Müller et al. (2003)	Denmark	Barley; Clover; Grass; Rape	Sandy	Temperate
42	Mungai and Motavalli (2006)	Kenya	Grass; Maize; Soyabean	clayey, Silt	Temperate
43	Murungu et al. (2011)	South Africa	Oat; Peas; Vetch	Sandy	Temperate
44	Nourbakhsh (2006)	Iran	Alfalfa; Wheat	Clayey	Subtropical
45	Pascault et al. (2010)	France	Alfalfa; Rape; Wheat	Clayey	Temperate
46	Quemada and Cabrera, (1995)	USA	Clover; Oat; Rye; Wheat	Sandy	Subtropical
47	Raiesi, (20065)	Iran	Alfalfa; Wheat	Clayey	Subtropical
48	Redin et al. (2014)	Brazil	Maize; Sorghum; Wheat, Soyabean; Sunflower; Vetch	Sandy	Tropical
49	Schmatz et al. (2017)	Brazil	Pea; Vetch; Wheat	clayey, sandy	Tropical
50	Shahande et al. (2011)	USA	Switchgrass	Silt	Subtropical
51	Shi et al. (2013)	Australia	Barley; Grass	Silt	Subtropical
52	Stewart et al. (20157)	USA	Maize; Sorghum; Soyabean; Sunflower; Wheat	Silt	Temperate
53	Vachon and Oelbermann (2011)	Argentina	Maize; Soyabean	Silt	Subtropical
54	Vahdat et al; (2010)	Iran	Alfalfa; Barley; Clover; Grass; Wheat	Clayey	Subtropical
55	Wang et al. (2004)	Australia	Brigalow; Grass; Sugarcane; Wheat	Sandy	Subtropical
56	Xu et al. (2006)	Australia	Alfalfa; Chickpea; Medic; Wheat	Sandy	Tropical
57	Zaccheo et al. (2002)	Italy	Alfalfa; Maize	Sandy	Temperate
58	Zeng et al. (2010)	China	Maize; Peanut; Poplar	Sandy	Temperate

Table 3: Crop quality, soils and environmental variables classification used in the study.

Variable	Variable remarks	Category	Symbol	Class	Ref.
Crop class	All different crop types categorised into four classes	Wheat, sorghum,	Crop class	Cereal,	Mathew, et al. (2017)
		grass,		Grass,	
		vetch bean, soyabean		Legume and	
		Canola, cotton		Oilseed	
Residue lignin concentration (%)	Initial lignin concentration of residues	<10	Lignin	Low	
		>10		High	
Residue lignin: N ratio	Residue lignin to nitrogen ratio	>10	lignin: N	High	
		<10		Low	
Residue C:N ratio	Crop residue carbon to nitrogen ratio	<20	C: N	Low	Puyuelo, (2011) and Probert (2005)
		20-30		Medium	
		>30		High	
Residue N concentration (%)	Initial nitrogen concentration of residues	>10	TN	High	
		<10		Low	
Residue C concentration (%)	Initial carbon concentration of residues	>50	TC	High	Abdalla et al., (2016)
		<50		Low	
Clay concentration (%)	Soil Texture based on clay fraction	>10	Soil texture	Clayey	Mathew et al., (2017) and Abdalla et al., (2016)
		20-32		Silt	
		<20		Sandy	
Soil pH concentration (CaCl₂)	Soil pH	<5.4	pH	Strongly acidic	Davies, 1971; Mathew et al. (2017)
		5.5-6.4		Slightly acidic	
		6.5-7.4		Neutral	
		>7.5		Alkaline	
Soil bulk density (g cm⁻³)	Average bulk density in soil profile	<1.3	BD	Low BD	Mathew et al., (2017)
		>1.3		High BD	
CEC (cmol_ckg)	Soil cation exchange capacity	>20	CEC	Low CEC	
		<20		High CEC	
Climate	Based on the average annual temperature and precipitation of the study site	>20	MAT	Tropical	Mutema et al., (2015) and Mathew et al., 2017
		>1500	MAP		
		20-10	MAT	Sub-tropical	
		100-1110	MAP		
		<10	MAT	Temperate	
		120-1000	MAP		

Table 4: Summary Statistics of plant, soil and environmental variables along with residue CO₂ emissions in different time period.

	Lignin	C:N	TC	TN	Clay	Sand	Silt	pH	SOC	MAP	MAT	C _R 30	C _R 90	C _R 120	1- [C _R 30/C _R 120]
	%				-----g kg ⁻¹ -----				%	mm	°C	-----mg CO ₂ -C g ⁻¹ C -----			
N	192	304	394	365	295	259	243	333	293	386	386	394	394	394	394
Mean	9.55	58.45	13.24	9.38	29.53	37.81	32.40	6.73	13.13	906.16	17.01	196.5	519.0	914.2	0.80
Median	7.70	39.16	1.15	4.00	25.30	32.00	28.00	6.80	9.50	656.00	17.00	138.0	415.6	795.0	0.80
Min.	0.02	7.80	0.04	0.01	2.00	1.00	1.00	3.87	0.50	89.40	3.90	0.3	1.1	3.2	0.49
Max.	29.40	409.00	165.76	407.00	77.30	96.00	83.00	8.60	39.00	2500.00	30.00	920.1	3205	3640	0.98
Q1	5.35	20.30	0.40	0.90	14.30	17.90	16.30	5.60	8.41	551.00	10.00	31.0	118.4	200.4	0.75
Q3	12.55	75.40	4.12	11.00	40.00	60.00	47.00	7.66	17.40	1095.00	24.00	304.9	858.9	1431.0	0.86
Variance	36.07	3257.25	1164.81	592.74	370.64	737.14	483.34	1.34	65.33	263814.21	46.19	37353.5	213397	585331	0.01
SD.	6.01	57.07	34.13	24.35	19.25	27.15	21.99	1.16	8.08	513.63	6.80	193.3	461.9	765.1	0.07
SE.	0.43	3.27	1.72	1.27	1.12	1.69	1.41	0.06	0.47	26.14	0.35	7.7	18.4	30.5	0.00
CV	63.30	98.10	13.70	262.70	64.90	75.40	67.60	17.30	61.60	56.50	40.30	98.4	89.0	83.7	9.11
Skewness	1.06	2.52	2.97	12.47	0.92	0.51	0.68	-0.30	1.04	1.15	0.10	1.07	1.10	0.73	-0.25
Kurtosis	0.83	8.30	7.69	197.12	0.13	-0.79	-0.32	-1.03	0.69	0.51	-1.12	0.58	2.11	-0.15	-0.23

Statistics: Min and Max =minimum and maximum, respectively. Q1 and Q3= first and third quartile, SD = standard deviation. C emission variables: C_R30; C_R90; C_R120 for cumulative residue CO₂ emissions to day 30, 90 and 120. Crop quality: lignin; C: N ratio; TC= total residue carbon; TN= total residue nitrogen. Soil variables: Clay concentration; sand concentration; silt concentration; soil pH (CaCl). SOC= soil organic carbon concentration; Climatic variables: MAP= mean annual precipitation; MAT= mean annual temperature. “†” values are not zero. but rounded off to one decimal place.

Table 5: Sample sizes of crop quality (n), soil and climatic factor categories in association with carbon emissions from residues.

		C _R 30			C _R 90			C _R 120			1-[C _R 30/C _R 120]		
		n	Mean	STDEV	n	Mean	STDEV	n	Mean	STDEV	n	Mean	STDEV
Overall		394	196.3	193.3	394	518.8	461.9	394	914.2	765.1	394	0.81	0.07
Crop type	Cereal	195	171.0	185.9	195	473.9	445.4	195	846.6	777.1	195	0.82	0.07
	Grass	54	217.0	185.8	54	529.7	426.7	54	946.8	741.0	54	0.79	0.06
	Legume	120	228.0	203.2	120	586.7	505.7	120	1003.0	758.3	120	0.78	0.08
	Oilseed	25	196.0	211.9	25	519.2	459.2	25	944.0	742.5	25	0.83	0.07
Residue lignin Concentration	High	73	173.0	165.2	73	457.0	402.3	73	816.9	694.2	73	0.80	0.07
	Low	119	218.0	188.9	119	602.3	524.3	119	1055.0	853.0	119	0.84	0.05
Residue C: N Ratio	High	142	144.9	159.0	142	447.0	424.9	142	837.9	777.4	142	0.78	0.07
	Low	103	273.7	223.4	103	686.9	537.4	103	1163.1	814.7	103	0.80	0.07
	Medium	59	201.1	214.7	59	484.9	449.7	59	856.8	734.8	59	0.80	0.08
TC	High	284	201.8	198.7	284	524.6	450.5	284	927.3	759.9	284	0.80	0.08
	Low	110	181.9	168.9	110	503.6	635.6	110	880.2	803.9	110	0.82	0.07
Soil texture	Clayey	121	224.4	179.0	121	587.5	440.7	121	1060.6	777.5	121	0.81	0.07
	Silt	130	191.1	215.6	130	505.8	523.9	130	894.3	819.4	130	0.82	0.08
	Sandy	137	178.2	184.7	137	454.7	417.8	137	789.9	699.2	137	0.79	0.08
Soil pH	Alkaline	133	178.1	170.0	133	487.2	410.7	133	869.2	712.5	133	0.82	0.07
	Neutral	57	195.4	165.4	57	532.3	362.0	57	919.4	613.8	57	0.79	0.07
	Slightly acidic	86	262.1	203.3	86	634.6	560.3	86	1140.2	874.0	86	0.78	0.07
	Strongly acidic	57	175.3	222.3	57	414.7	443.4	57	709.9	687.7	57	0.79	0.09
Soil organic carbon Concentration	High	39	149.4	148.9	39	356.7	529.6	39	591.4	695.8	39	0.81	0.07
	Low	153	157.5	188.9	153	421.3	430.9	153	746.9	725.8	153	0.81	0.07
	Medium	101	230.3	184.9	101	595.2	432.0	101	1066.4	746.6	101	0.81	0.07
Climate	Subtropical	198	192.5	181.8	198	522.8	427.3	198	912.2	736.5	198	0.81	0.07
	Temperate	101	149.8	213.8	101	430.3	536.5	101	779.7	828.1	101	0.82	0.08
	Tropical	95	253.4	193.7	95	604.5	444.7	95	1061.2	755.8	95	0.78	0.08

Table 6: Sample sizes of crop type categories associated with residue carbon emission variables.

Crop type	Crop	C _R 30			C _R 90			C _R 120			1-[C _R 30/C _R 120]		
		n	Mean	STDEV	n	Mean	STDEV	n	Mean	STDEV	n	Mean	STDEV
	Overall	394	196.3	193.3	394	518.8	461.95	394	914.2	765.07	394	0.81	0.07
Cereal	Barley	9	177.7	156.8	9	547.2	436.1	9	1005	778.6	9	0.84	0.05
	Maize	59	85.8	124.3	59	275.1	319.8	59	495.0	541.7	59	0.84	0.08
	Oat	8	212.1	190.8	8	501.9	425.5	8	872.7	724.5	8	0.79	0.06
	Rice	10	251.9	255.7	10	657.1	662.3	10	1211	1196.6	10	0.82	0.08
	Rye	12	199.3	190.8	12	501.6	453.5	12	824.2	729.5	12	0.77	0.04
	Sorghum	16	261.1	218.8	16	714	496.7	16	1303	855.9	16	0.83	0.08
	Wheat	81	196.3	194.8	81	533.6	452.3	81	950.7	791.8	81	0.81	0.07
Grass	Grass	54	217	184.9	54	529.7	420.3	54	946.8	734.2	54	0.79	0.06
Legume	Alfalfa	24	359.0	262.7	24	796.0	515.0	24	1319.0	801.0	24	0.76	0.07
	Bean	12	223.7	239.9	12	538.7	471.0	12	962.1	667.0	12	0.80	0.06
	Clover	26	184.2	139.6	26	580.6	661.0	26	940.3	866.5	26	0.78	0.06
	Pea	27	184.2	152.7	27	452	343.8	27	809	554.1	27	0.78	0.07
	Soyabean	23	207.8	157.0	23	577.5	401.7	23	1039	715.6	23	0.81	0.10
	Vetch	8	190.2	182.6	8	531.1	433.4	8	870.4	696.1	8	0.80	0.05
Oilseed	Canola	8	293.5	327.3	8	670.5	717.3	8	1211	1184.5	8	0.79	0.07
	Cotton	9	135.5	98.8	9	442.5	281.0	9	841.1	513.9	9	0.85	0.03
	Sunflower	8	166.5	208.7	8	454.2	451.7	8	792.5	667.4	8	0.84	0.10

C_R30, C_R90 and C_R120=Amount of CO₂ emitted from crop residues to day 30, 90 and 120 of the experiment, respectively.

Table 7: Correlation matrix statistic table of plant, soil and climatic influence on residue CO₂ emissions.

	Lignin	C:N	TC	TN	Clay	Sand	Silt	pH	SOC	MAP	MAT	CR30	CR90	CR120	$\frac{1-}{[CR30/CR120]}$
Lignin	1.00														
C:N	0.15	1.00													
TC	-0.06	-0.06	1.00												
TN	0.03	-0.19	-0.02	1.00											
Clay	-0.08	-0.11	0.51*	-0.19	1.00										
Sand	-0.02	-0.15	-0.42	0.32*	-0.64*	1.00									
Silt	0.10	0.30*	-0.02	-0.19	-0.26*	-0.57*	1.00								
pH	0.02	0.15	0.16	-0.63*	0.26*	-0.45*	0.29*	1.00							
SOC	-0.03	0.03	0.23*	-0.10	0.31*	-0.37*	0.14	-0.08	1.00						
MAP	-0.02	-0.03	-0.16	0.19	-0.41*	0.4*	-0.07	-0.58*	-0.20	1.00					
MAT	0.00	-0.20	-0.21	0.16	-0.40*	0.41*	-0.08	-0.40*	0.03	0.43*	1.00				
CR30	-0.08*	-0.14*	0.59*	-0.22	0.34*	-0.38*	0.12	0.38*	0.15	-0.31*	0.07	1.00			
CR90	-0.11*	-0.10*	0.46*	-0.28*	0.26*	-0.32*	0.13	0.44*	0.09	-0.32*	0.10	0.96*	1.00		
CR120	-0.12*	-0.09*	0.40*	-0.26*	0.22	-0.29*	0.14	0.42*	0.07	-0.31*	0.10	0.93*	0.99*	1.00	
$\frac{1-}{[CR30/CR120]}$	0.15	-0.07*	0.37*	0.11	0.10	-0.12	0.05	-0.19	0.27*	0.19	0.21	0.27*	0.07	-0.03	1.00

Residue CO₂ emission to day 30, 90 and 120 of the experiment. lignin: residue lignin concentration; C:N: residue carbon to nitrogen ratio; TC: Initial residue carbon concentration; Clay, sand & silt: soil texture based on clay fraction (%clay); pH: soil pH (KCl); SOC: soil organic carbon concentration; MAP&MAT: climatic factors-mean annual precipitation and mean annual temperature. * Significant at p<0.05.

Table 8: Proportion of data points with “priming”, i.e. with a 120 days cumulative C-CO₂ emissions above the amount of C added to the soil.

Crop	%
Alfalfa	58
Barley	44
Bean	25
Canola	63
Clover	27
Cotton	44
Grass	48
Maize	25
Oat	50
Pea	33
Rice	50
Rye	58
Sorghum	56
Soyabean	48
Sunflower	25
Vetch	38
Wheat	36
<i>Mean</i>	43