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1 Mixing ratio and N fertilization drive synergistic effects between biochar and  
2 compost

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37 **Abstract**

38 Compost and biochar are increasingly considered to improve crop growth and soil functioning in  
39 agriculture. However, their combined application has shown contrasting results, probably resulting from  
40 the use of different biochar/compost ratios and divergent (synergistic or antagonist) impacts on nutrient  
41 availability, especially nitrogen (N). We aim to elucidate how biochar/compost mixtures affect nutrient  
42 availability and plant growth. We hypothesised that biochar and compost will have a synergistic effect,  
43 which will depend on the biochar/compost ratio, consequently impacting nutrient uptake and biomass  
44 of plants. In this context, ryegrass was grown on agricultural soil amended with five compost/biochar  
45 ratio mixtures with(out) N fertilisation. We followed soil fertility parameters, soil microbial carbon (C)  
46 and N, nutrient uptake, and plant growth. Results showed that irrespective of their ratio in the mixture,  
47 applying biochar and compost had no effect on microbial biomass but increased soil nitrate  
48 concentration, suggesting that, despite their high C/N ratios, amendments increase N availability while  
49 preventing microbial immobilisation. Plant biomass and nutrient uptake improvements by the  
50 amendments depended on their ratio. Plant stoichiometric analysis revealed that a mixture containing  
51 less biochar than compost reduced N limitation and was even more effective than the sole application of  
52 chemical N fertiliser. The beneficial effects of biochar and compost on plant growth were strengthened  
53 with N fertilisation. In conclusion, we demonstrated synergistic effects between biochar and compost,  
54 predominantly driven by their mixing ratio, to reduce N limitation in the soil towards a more nutrient-  
55 equilibrated system and highlighted their potential use as a sustainable alternative or supplement to  
56 chemical fertilisers.

57

58 **Keywords**

59 Biochar; Compost; Soil fertility; Sustainable solutions; Synergism

60

61 **Highlights**

62 Several biochar/compost mixtures were tested

63 Synergism was found between biochar and compost

64 Best performances were found with 30% biochar and 70% compost

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66

## 1. Introduction

67 The exponential rise of the population is associated with increasing consumption and demand for  
68 agricultural products (Kopittke et al., 2019). To improve yields, the use of mineral fertilisers increased  
69 exponentially throughout the world over the last decades (Savci, 2012), and led to disruptions of  
70 biogeochemical cycles with deleterious financial and environmental impacts (El-Naggar et al., 2019;  
71 Laghari et al., 2016; Tei et al., 2020). Excessive fertilisation has adverse effects on soil microbial  
72 communities (Savci, 2012) and may also be a threat for water quality due to high N and P losses to  
73 aquatic systems (Savci, 2012; Tei et al., 2020). Consequently, there is a need to find more sustainable  
74 and cost-effective materials to supply nutrients to plants (Igalavithana et al., 2015). One possibility is to  
75 apply organic amendments, which not only supply nutrients, but also improve the overall soil quality  
76 (Diacono and Montemurro, 2010; Siedt et al., 2021) and may be beneficial for soil organic carbon (SOC)  
77 sequestration (Chabbi et al., 2017; Védère et al., 2023). Among the different potential organic  
78 amendments, biochar and compost are the subject of many studies due to their ability to improve soil  
79 fertility and the SOC content.

80 Compost is a stabilised product, rich in organic matter, resulting from the microbial degradation  
81 of organic wastes (Diacono and Montemurro, 2010; Kammann et al., 2016). The composting process  
82 reduces the amount of organic wastes as the majority is mineralised and the resulting material can be  
83 used for soil amendment. However, at the end of the process, not all materials are composted, and  
84 compost refusals are leftovers, which still need to be disposed. To further reduce waste in the context of  
85 a circular economy, they can be pyrolyzed to produce biochar in a cost-effective and sustainable process,  
86 which, to our knowledge, is a so far neglected possibility.. Biochar is a stable and carbon-rich product,  
87 having a high surface area and porosity, utilised as a soil amendment in degraded environments to  
88 improve soil physical and chemical properties (Chen et al., 2019; Karim et al., 2022). However, biochar  
89 and compost being possibly done with a wide variety of materials present a large panel of properties that  
90 can greatly differ amongst each other (Abbott et al., 2018).

91 Previous studies have hypothesised that combining nutrient rich compost with biochar will  
92 induce synergistic effects on the soil quality, nutrient supply, microbial activity and ultimately plant  
93 growth (Kammann et al., 2016; Radin et al., 2018). Indeed, compost contains organic matter, can be rich  
94 in nutrients and stimulate microbial activity, but is easily decomposable and subject to rapid loss. On  
95 the other hand, biochar is a more stable product with generally a low nutrient content but with the  
96 potential to sorb those present around and eventually release them to the plant during its growth. Biochar,  
97 as a very porous material, can also serve as a habitat by microorganisms (Chen et al., 2019). Previous  
98 studies applying biochar and compost in combination showed contrasting results, with positive, neutral  
99 or negative effects of the combined treatments compared to the single ones. More precisely, a higher  
100 plant biomass and nutritious state and higher organic carbon was found by (Abbas et al., 2020) when  
101 applying a combination of biochar and compost at a 1:1 ratio, whereas (Doan et al., 2015) applied a  
102 mixture of biochar and compost at a ratio 1:3 and found a higher soil N content and maize yield than the

103 single amendments. No difference between the single and combined biochar/compost treatments were  
104 observed in the study of (Aubertin et al., 2021) (biochar:compost ratio of 1:5) in term of ryegrass  
105 biomass, and in the study of (Trupiano et al., 2017) (biochar:compost ratio of 1:3) in term of lettuce  
106 biomass and soil nutrient contents. Finally, negative effects of the mixture were observed by (Libutti  
107 and Rivelli, 2021) on plant biomass and nutritious state when applying a mixture of biochar and compost  
108 at a ratio of 1:1.2, and by (Seehausen et al., 2017) (biochar:compost ratio of 1:2) in terms of plant height  
109 and leaf area while biomass production was similar in the single and combined treatments.

110 These studies show no clear trend on the best ratio between biochar and compost, and potential  
111 synergism, to improve soil and plant. Furthermore, most of the cited studies tested only one  
112 biochar/compost ratio. The potential synergistic effect between biochar and compost may be highly  
113 dependent on the ratio between recalcitrant and labile carbon (C) compounds and thus the effect of  
114 different proportions of biochar and compost in the mixtures needs to be evaluated. In fact, one of the  
115 possible limitations about the use of biochar could be its potential negative effect on plant N availability,  
116 although it was shown to have beneficial effects on K availability (Nobile et al., 2022). When applied  
117 to soil, due to its high proportion of C relative to N, biochar can induce a microbial immobilisation of N  
118 (Abbas et al., 2020; Chen et al., 2021; Schofield et al., 2019) even though this effect depends on the type  
119 of biochar and its C mineralisation potential (Nguyen et al., 2017). As a result, additional mineral N  
120 fertilisation may be required when biochar is added to the soil to avoid N deficiency in plants due to N  
121 immobilisation by microorganisms and sustain crop production (Iglesias-Jimenez and Alvarez, 1993; Li  
122 et al., 2022). On the other hand, (Dakora and Phillips, 2002) showed that biochar C/N ratio was a poor  
123 predictor of soil N mineralisation and that, unexpectedly, biochar tended to raise N mineralisation  
124 potential in soil by inducing a priming effect.

125 In this study, we aim at gaining insight into the impact of biochar and compost mixed at different  
126 ratios on nutrient availability and plant growth. For this purpose, we investigated the effect of five  
127 biochar/compost mixtures on (i) soil chemical properties, (ii) nutrient availability, and (iii) plant growth,  
128 under two N fertilisation regimes. We monitored aboveground ryegrass growth, above- and  
129 belowground nutrition status of the plants after three harvests. We hypothesised that (i) combining  
130 biochar and compost will have induce a synergistic effect and thus a higher improvement of soil fertility  
131 and plant growth than the two amendments applied alone, and (ii) the intensity of the synergistic effect  
132 will depend on the ratio between biochar and compost and the nitrogen fertilisation .

133

## 134 **2. Materials and Methods**

### 135 **2.1. Soil and amendments**

136 Soil was collected from an experimental site based at the UniLaSalle campus, in Beauvais (Oise,  
137 France) at the following GPS coordinates: 49°25'49" N, 2°04'51" E. It was classified as a silt loam  
138 Haplic Luvisol. Samples were taken at 0-10 cm depth and sieved at 5 mm before being used.

139 The compost was a green waste compost (grass, poplar, and conifer branches) sampled at the  
140 platform of Fervivert (Seine-Maritime, France), being the result of a 4-month-thermophilic phase and 2-  
141 month-maturation process.

142 The non-composted residues generated by the production of the above-mentioned compost were  
143 used to produce biochar. Those residues were predominantly made of the non-composted tree branches.  
144 Pyrolysis took place in an industrial pyrolysis reactor (Biogreen® Pyrolysis Technology, ETIA, Oise,  
145 Haut-de-France, France) without oxygen, at 450 °C for 10 min.

146 Initial soil, compost, and biochar characteristics have been previously assessed (Nobile et al.,  
147 2022, 2020; Védère et al., 2023) and are presented in Table 1.

148  
149

## 150 **2.2. Experimental design**

151 A two factorial pot experiment was performed using the soil, the two amendments, and a N  
152 fertiliser solution. The first factor was “amendment” and the second was “fertilisation”.

153 For the “amendment” factor, biochar and compost were applied together in the soil at five  
154 different mixing ratios (Table S1): (i) BC100, corresponded to pure biochar (ii) BC70CP30,  
155 corresponded to a combination of biochar and compost at a ratio of 70:30 (on a dry weight (dw) basis)  
156 (iii) BC50CP50, corresponded to a combination of biochar and compost at a ratio of 50:50 (on a dw  
157 basis) (iv) BC30CP70 corresponded to a combination of biochar and compost at a ratio of 30:70 (on a  
158 dw basis) and (v) CP100, corresponded to pure compost. Amendment application rate was 10 t ha<sup>-1</sup> in  
159 every treatment (considering an application at 5 cm). A control without amendment was also prepared.  
160 Considering the properties of the amendments, the mixtures added different quantities of N, P and K: (i)  
161 BC100 added 8.4 kg.ha<sup>-1</sup> N, 37 kg.ha<sup>-1</sup> P, and 179 kg.ha<sup>-1</sup> K; (ii) BC70CP30 added 87 kg.ha<sup>-1</sup> N, 39  
162 kg.ha<sup>-1</sup> P and 176 kg.ha<sup>-1</sup> K; (iii) BC50CP50 added 139 kg.ha<sup>-1</sup> N, 40 kg.ha<sup>-1</sup> P and 174 kg.ha<sup>-1</sup> K; (iv)  
163 BC30CP70 added 191 kg.ha<sup>-1</sup> N, 41 kg.ha<sup>-1</sup> P and 173 kg.ha<sup>-1</sup> K; and (v) CP100 added 270 kg.ha<sup>-1</sup> N,  
164 42 kg.ha<sup>-1</sup> P and 170 kg.ha<sup>-1</sup> K. Based on these values, the treatment CP100 presents the highest nutrient  
165 content and should thus lead to the highest biomass production, if no synergism occurs between biochar  
166 and compost.

167 For the “fertilisation” factor, half of the pots were fertilised (treatments noted Fert+) with a N  
168 solution, in the form of ammonium-nitrate, corresponding to 70 N units.ha<sup>-1</sup>, while distilled water was  
169 applied to the other half (treatments noted Fert-). N fertiliser was applied after amendments were mixed  
170 with the soil and substrates were placed in the pots, and one week before sowing.

171 In total, this two factorial design had 12 treatments (Table S1) and all treatments were repeated  
172 five times. Plastic pots (8 cm diameter, 7 cm height) were filled with 450 g of soil (dw basis) and the  
173 amendments and were randomly arranged in a greenhouse with controlled conditions (photoperiod 16 h  
174 light/8 h dark, light intensity of 10 W.m<sup>-2</sup>, temperature of 21 °C). Before sowing, soils with and without  
175 amendments were equilibrated during one week at 80 % water holding capacity.

176 After substrate equilibration, a subsample of soil was taken in three replicates and was analysed  
177 (Centre provincial de l'Agriculture et de la Ruralité, La Hulpe, Belgium) for pH (in KCl, ISO 10390),  
178 total N (Dumas method), ammonium-N and nitrate-N contents (KCl extraction), available P and K  
179 concentrations (ammonium acetate + EDTA extraction), organic C content (dry combustion NF ISO  
180 14235) and C/N ratio. Then, 0.5 g of seeds of ryegrass (*Lolium multiflorum*) were sown in each pot and  
181 plants were allowed to grow for three months (13 weeks). During those 13 weeks, substrates were  
182 maintained at 80 % water holding capacity through regular watering (every two days) based on mass  
183 loss and thus no leaching was observed.

184

### 185 **2.3. Soil pore water sampling and analysis**

186 Soil pore water (SPW) was sampled (8 mL volume) with a rhizon sampler (model MOM,  
187 Solutions Technologiques pour l'Environnement, Reignac sur Indre, France) placed into the soil at the  
188 beginning of the experiment. Sampling had been done before (T0) and four, eight and 13 weeks after  
189 sowing (T4, T8 and T13, respectively) by applying a pressure on the soil moisture sampler using vacuum  
190 tubes (Solutions Technologiques pour l'Environnement,Reignac sur Indre, France). pH was immediately  
191 measured with a pH meter (Metler Toledo, Seven Easy).

192

### 193 **2.4. Plant harvest and analysis**

194 Each month after the start of the experiment, the aerial parts of the plants were harvested by  
195 cutting all the biomass at 1 cm above the soil level. Plant shoots were dried at 50 °C for two days and  
196 weighed to determine their dry biomass.

197 At the end of the experiment (*i.e.*, 13 weeks after sowing), plants were harvested and, following  
198 the removal of the aerial part of the plants, soil and roots were gently separated. Roots were washed with  
199 water, dried for two days at 50 °C and then carefully manually cleaned in order to remove all the possible  
200 remaining soil, compost and biochar particles. Root biomass could not be determined due to a too  
201 important biomass loss during the harvest.

202 Shoot (from the three harvests) and root (from the last harvest) materials were grounded in order  
203 to analyse their C and N content using an elemental analyser (Vario Isotope Select, Elementar, Hanau,  
204 Germany) and acid digested in a microwave in order to determine their P and K concentrations using  
205 inductively coupled plasma mass spectrometry (Thermo Scientific iCAP 6000 Series). Using those  
206 concentrations, C/N and N/P ratios were calculated.

207

### 208 **2.5. Soil sampling and analysis**

209 Once plants were harvested and roots removed from soil, the soil was sampled and separated in  
210 two sub-samples. The first sub-sample was kept at -20 °C (to conserve the chemical state of the  
211 substrates) until further analysis. The second sub-sample was stored at 4 °C and microbial biomass was  
212 extracted within 48 h.

213 Similarly to the analysis at sowing time, the soils sampled at the end of the experiment and  
214 stored at -20°C were analysed for pH, electrical conductivity, total N, ammonium-N content, nitrate-N  
215 content, available P, and K concentrations, organic C content and C/N ratio. The methods used were the  
216 same as described previously.

217 In addition, the soils were also analysed for microbial biomass C and N, using the chloroform  
218 fumigation method (Vance et al., 1987): 6 g of chloroform fumigated and non-fumigated soil were  
219 extracted with 40 mL of a K<sub>2</sub>SO<sub>4</sub> solution (0.05 M). After 30 min, solutions were centrifuged and filtered  
220 (0.45 µm). The K<sub>2</sub>SO<sub>4</sub> extracts were frozen, freeze dried and their C and N content was determined using  
221 an elemental analyser (Vario Isotope Select, Elementar, Hanau, Germany). The difference between  
222 fumigated and non-fumigated soils was used as the microbial C or N flush, and converted to microbial  
223 biomass C and N, using the following equations (Beck et al., 1997; Lovell et al., 1995):

$$(2) \text{ Microbial C} = \text{C flush} \times 2.22$$

$$(3) \text{ Microbial N} = \text{N flush} / 0.5$$

## 227 2.6. Statistical analysis

228 All data were analysed using the R software, version 3.5.1. First, the normality of the data was  
229 evaluated using the Shapiro test. Thereafter, the homogeneity of variance was assessed using either the  
230 Bartlett test (for normal data) or the Fligner test (for non-normal data). Finally, means were compared  
231 using the Anova test, when data distributions were parametric, or the Kruskal-Wallis test, when data  
232 distributions were not parametric, followed by a post-hoc test, *i.e.*, Tukey test or Dunn test, respectively.  
233 In addition, the effect of amendment, fertilisation and amendment\*fertilisation was assessed using two-  
234 way Anova or Adonis tests. Difference was considered significant at  $p < 0.05$ .

## 235 3. Results

### 236 3.1. Soil properties and pore water pH

237 Following amendment applications, pH, total N, nitrate-N, organic C, C/N, available P and K  
238 increased, while ammonium-N content decreased (Table 2 and Table S2). Nitrogen fertilisation only  
239 affected nitrate-N concentration, which increased in the fertilised pots compared to non-fertilised ones.  
240 Finally, the interaction amendment\*fertilisation only had a significant effect on the ammonium-N  
241 concentration. The highest values were observed when BC100/-Fert was applied for pH, organic C, C/N  
242 and available P, when CP100/-Fert was applied in the case of total N and available K, while the ratio  
243 BC50CP50/Fert+ showed the highest nitrate-N concentration.

244 After the end of the experiment, amendment application had a significant effect on all soil  
245 chemical properties, except pH and nitrate-N content (Table 3 and Table S2). All those affected soil  
246 properties (total N, ammonium-N, organic C, C/N, available P and K) were increased by amendment  
247 application, except ammonium-N content. OC and C/N ratios showed no differences between the  
248 different biochar-compost mixtures. BC100 treatments showed the highest available P, CP100 the  
249



250 highest total N and both treatments had similar and high available K concentrations compared to the  
251 controls and mixtures.

252 At the end of the experiment, microbial biomass C (MBC) and N (MBN) were 0.21 mg.g<sup>-1</sup> and  
253 0.024 mg.g<sup>-1</sup>, respectively, on CT/Fert- (Figure S1a and 1b) and they were not affected by any of the  
254 amendments.

255 Before the start of the experimentation, the pH measured in soil pore water (SPW) of the control  
256 (CT/Fert-) was 7.61 (Figure S2), and increased in the latter sampling times to reach a value of 8.69.  
257 Amendments significantly affected SPW pH in the first three samplings but had no effect at the harvest  
258 time (T13) (Table S2). Amendments tended to decrease SPW pH at T0 (values ranging from 7.08 to  
259 7.53) and T8 (values ranging from 7.80 and 8.45), while an increase was noted at T4 (values between  
260 7.61 and 7.95). Fertilisation only affected SPW pH at the initial time, and induced a reduction of SPW  
261 pH, which was less strong when amendments were applied. The interaction amendment\*fertilisation had  
262 a significant effect on SPW pH at all sampling times except the T0.

263

### 264 **3.2. Plant biomass**

265 After each harvest, the plant biomass in the control treatment were respectively 1.18 g, 0.42 g  
266 and 0.51 g (Figure 1). Plant biomass was significantly affected by amendment and fertilisation (Table  
267 S3). Plant biomass was positively and significantly affected by the interaction of amendments with  
268 fertiliser addition during the first and second harvest. All the organic amendments, independently of the  
269 fertiliser application, increased the plant aerial biomass following the order: CT < CP100 < BC100 <  
270 BC70CP30 < BC50CP50 < BC30CP70 during the two first harvests. After the third harvest the addition  
271 of amendment only significantly increased the biomass in the case of BC30CP70 and CP100 treatments,  
272 irrespective of the presence or the absence of N fertiliser. The positive effect of fertiliser addition was  
273 observed after the first and the second harvest (except for CP100) and only observed in the  
274 BC30CP70/Fert+ treatment during the last harvest. After the three different harvests the highest biomass  
275 was always recorded for the BC30CP70/Fert+ modality with 3.01 g, 1.21 g and 0.72 g respectively.

276 Finally, the total aerial biomass collected by the end of the experiment was 2.10 g in the control  
277 treatment (CT/Fert-) (Figure 1). Total aerial biomass production was significantly affected by  
278 amendment, fertilisation and their interaction (Table S3). Amendment application increased biomass in  
279 all the treatments as well as fertiliser addition. Fertilisation allowed for a higher biomass increase in  
280 treatment without compost (+48.9 % and +52.5 % biomass respectively in CT/Fert+ and BC100/Fert+)  
281 and a lower biomass increase in the two treatments most rich in compost (+19.2 % and +31.3 % biomass  
282 respectively in BC30CP70/Fert+ and CP/Fert+). Most total aerial biomass was recorded for the  
283 treatment BC30CP70/Fert+.

284

### 285 **3.3. Carbon and macronutrient concentrations (N, P and K) in the plants**

286 At the first harvest, amendment application had a significant effect on C, N, P and K , while  
287 fertilisation affected N and P concentrations and the interaction amendment\*fertilisation affected N and  
288 K concentrations (Table S3). In more detail, C values ranged from 395.4 g.kg<sup>-1</sup> (CP100/Fert-) to 442.2  
289 g.kg<sup>-1</sup> (BC50CP50/Fert-) in the amended conditions, although they were not different from the control.  
290 The N concentrations were increased by the addition of some mixture up to 2-fold (BC30CP70/Fert+).  
291 The plants' P concentrations were decreased by the biochar amendments and fertilisation up to -34%  
292 (BC30CP70/Fert+). Finally, K concentrations were increased by the amendments up to +16%  
293 (BC30CP70/Fert+).

294

295 At the second harvest, amendment application significantly affected all parameters. Fertilisation  
296 affected all elements except K concentrations while the interaction amendment\*fertilisation only  
297 significantly affected N and P concentrations (Table S3). Carbon concentrations increased with  
298 amendments and fertilisation up to +2 % (Figure S3) (BC30CP70/Fert+). Nitrogen and P concentrations  
299 were both decreased when amendments and fertilisation were applied, except for P when CP100 was  
300 used (Figures 2 and 3). More specifically, N concentrations in plants grown on the amended substrates  
301 decreased down to -21% (BC100/Fert+), whereas P concentrations decreased down to -20%  
302 (BC30CP70/Fert-). Finally, K concentrations were only increased in the presence of CP100 up to +38  
303 % (Fert-) and +58 % (Fert+) (Figure 4).

304

305 At the last harvest, the application of the organic amendments significantly affected C, N, P and  
306 K concentrations, fertilisation affected only N, P and K concentrations while the interaction  
307 amendment\*fertilisation had no effect compared to control (Table S3 ). The carbon concentrations of  
308 harvested biomass were increased by the addition of organic amendments up to +6 % (CP100/Fert-)  
309 (Figure S3); N concentrations were not significantly changed by amendment addition (Figure 2) .  
310 Phosphorus concentrations decreased with the addition of amendment and fertilisation, to reach values  
311 down to -34 % (Figure 3) (BC30CP70/Fert+). Finally, K concentrations were again only increased  
312 when CP100 was applied, with values up to +9 % on average (Figure 4).

313

314 Roots were also analysed for their element concentrations, and in general, amendment,  
315 fertilisation and amendment\*fertilisation had no effect on root element concentrations, except for K  
316 (Table S4 ). Concentrations varied between 319.5 g.kg<sup>-1</sup> (CP100/Fert-) and 365.5 g.kg<sup>-1</sup> (BC100/Fert+)  
317 (Table S5 ) for C, 6.2 g.kg<sup>-1</sup> (CT/Fert+) and 7.0 g.kg<sup>-1</sup> for N (BC30CP70/Fert+ and CP100/Fert+). P  
318 concentrations ranged from 698 mg.kg<sup>-1</sup> (CT/Fert-) to 942 mg.kg<sup>-1</sup> (BC100/Fert+) and K concentrations  
319 from 3.4 g.kg<sup>-1</sup> (CT/Fert- and BC30CP70/Fert+) to 4.8 g.kg<sup>-1</sup> (BC100/Fert+).

320

321

### 3.4. Element stoichiometry of aboveground and belowground plant tissue

322 For aerial tissue, at the first harvest, the C/N ratio was 51.80 in the control without fertiliser  
323 (CT/Fert-) (Figure 5a) and the N/P ratio was 3.02 (Figure 5b). Amendment, fertilisation, and  
324 amendment\*fertilisation significantly affected both ratios (Table S3). The C/N ratio tended to decrease  
325 after amendment, with values ranging from 28 (BC30CP70/Fert+) to 53 (BC70CP30/Fert-), while N/P  
326 ratio increased and reached values between 2.9 (CP100/Fert-) and 8.7 (BC30CP70/Fert+). Similar trends  
327 were observed following fertilisation, *i.e.*, decrease of the C/N ratio and increase of the N/P ratio.

328 At the second harvest, for the non-fertilized and non-amended control (CT/Fert-), shoot C/N  
329 ratio was 57.96 and shoot N/P ratio was 2.00 (Figures 5a and 5b). Amendments significantly increased  
330 C/N ratio and decreased N/P ratio, with values ranging respectively from 55 (CP100/Fert-) to 74  
331 (BC100/Fert+) and from 1.75 (BC70CP30/Fert-) to 2.1 (BC30CP70/Fert+). Fertilisation and  
332 fertilisation\*amendment only significantly affected C/N ratio (Table S3).

333 At the last harvest, the shoot C/N and N/P ratio values for CT/Fert- were 55.07 and 3.23,  
334 respectively (Figures 5a and 5b). Amendment applications tended to significantly increase both ratios  
335 and values ranged between 55 (CP100/Fert+) and 64 (BC30CP70/Fert+) for C/N, and between 3.4  
336 (BC100/Fert-) and 4.4 (BC30CP70/Fert+) for N/P.

337 At the end of the experiment, root C/N ratio was 50.4 on the non-fertilised control, and none of  
338 the treatments (amendments and fertilisation) affected root C/N ratio (Table S5 ). The root N/P ratio  
339 was 8.0 on CT/Fert-, and none of the other treatments showed significant difference with the control  
340 (Table S5).

341 The results of the element stoichiometry in plant tissue identify the ratio BC30CP70 as the  
342 optimum for a reduction of N limitation (decrease C/N and increase N/P).

343

#### 344 **4. Discussion**

345 Although the combination of biochar and compost has been often studied to improve the fertility of  
346 agriculture soils, the importance of the ratio between those two organic amendments still lacks proper  
347 evaluation. Our study focused its objectives in assessing the influence of this ratio and determining the  
348 optimal ratio. We have demonstrated an additive effect of biochar and compost combination on the soil  
349 fertility (in particular nutrient content and availability) while combining biochar and compost induced a  
350 synergistic effect on plant growth and nutrition. Finally, we showed that the grade of this synergistic  
351 effect was highly influenced by the ratio between biochar and compost, with the treatment containing  
352 30 % biochar and 70 % compost having the best effects.

353

#### 354 **4.1. The soil fertility improvement is driven by the compost proportion, in an additive** 355 **interaction between biochar and compost**

356 Addition of biochar and compost to the soil increased its organic C concentrations directly after the  
357 amendment application and until the end of the experiment, between 25 % and 60 %. This was expected

358 as the addition of organic amendment, such as biochar and compost, is often shown to raise SOC rapidly  
359 after their application (Agegnehu et al., 2016, 2015; Chan et al., 2007; Fischer and Glaser, 2012). An  
360 interesting result regarding SOC was that soil MBC measured in soils at the end of the experiment was  
361 not impacted by amendment application, which is inconsistent with results obtained by other authors  
362 (Irfan et al., 2019; Li et al., 2020; Liu et al., 2021). Indeed, after soil application, compost usually  
363 stimulates soil microbial communities, which in turn impacts biogeochemical cycling and plant growth  
364 (Abbott et al., 2018). Similarly, biochar has often beneficial effects on soil microorganisms by providing  
365 a microhabitat (Lehmann et al., 2011), protecting them from predation and allowing a good water  
366 retention in its microporosity protecting them from desiccation (Abbott et al., 2018). MBC is generally  
367 increased after biochar application particularly at low pH soil ( $< 6.5$ ) (Pokharel et al., 2020).  
368 Nevertheless, in our experiment where soil pH was 7.9, MBC was unchanged by the amendment  
369 applications after 13 weeks, suggesting that the growth conditions for microbial soil communities were  
370 similar in all treatments at the end of the experiment. Such non-effect could be related to the fact that  
371 water was provided at optimal rate, and thus microorganisms did not particularly need protection from  
372 desiccation (Griffins, 1981; Young et al., 2008). As well, MBC was unfortunately measured only 13  
373 weeks after the amendment application, and it is not sufficient to ensure that the added substrates had  
374 no effect on microorganisms' development. Otherwise, measurements of soil gas emissions during such  
375 experimentation could have brought more insights on possible microbial activities.

376 The addition of the biochar-compost mixtures increased the total content and availability of the  
377 macronutrients nitrogen (from 11 % to 36 %), phosphorus (from 10 % to 84 %) and potassium (from 11  
378 % to 65 %). Similar amelioration of soil organic matter and nutrient contents has been previously  
379 observed following the application of compost and biochar, and related to the amendment properties  
380 (high organic matter and available nutrient contents) (Plaza et al., 2016; Radin et al., 2018; Ravanbakhsh  
381 et al., 2019). However, an immobilisation of N following the addition of amendments with high C/N  
382 ratio has also been often observed, especially in the case of biochar (Bong Cassendra Phun Chien et al.,  
383 2021; Jien et al., 2018). One of the reasons for such immobilisation is a sorption of N on the biochar  
384 surface (Garbowski et al., 2023; Jien et al., 2018) and, more importantly, its incorporation into the  
385 microbial biomass (Irfan et al., 2019). Although it was unfortunately not possible to assess it at the early  
386 stages of our experimentation, at the end of our study, the application of biochar and compost did not  
387 show any microbial immobilisation of N, as shown by the lack of effects of organic amendment  
388 application on MBN after 13 weeks, which is likely related to the lack of change in MBC. When biochar  
389 and/or compost are applied to the soil, the mineralisation of the labile C by microorganisms may, in the  
390 short term, induce a microbial immobilisation of the available soil N, resulting in higher MBN (Abbas  
391 et al., 2020; Chen et al., 2021; Schofield et al., 2019). Nitrogen incorporated into the microbial biomass  
392 is not available for plants, which could consequently reduce their growth. For these two reasons, it has  
393 been recommended to apply, together with an organic C-rich amendment such as biochar or compost, a  
394 chemical N fertilisation to compensate for the N immobilisation, as N coming from chemical fertilisation

395 is directly available for plants although rapidly depleted, while the one from organic amendments will  
396 require more time to be available (Dey and Mavi, 2021; Gao et al., 2019). By contrast, adding biochar  
397 and/or compost increased total N in the soil (from 11 % to 36 %) and, more importantly, the  
398 concentration of nitrate-N at initial time (between 1.8 and 5.6 times), which might be due to the direct  
399 release of nitrate-N by amendments and to higher nitrification (Clough et al., 2013; Zhang et al., 2021).  
400 We hypothesise that adding biochar and/or compost improved the availability of N, and thus could  
401 ameliorate plant growth, as nitrate is the form of N preferentially taken up by plants. Our results  
402 confirmed this hypothesis, as the ryegrass biomass increased in the amended conditions, under both N  
403 fertilisation conditions, although the increase diminished with the repeated harvests. Previous studies  
404 have also shown that following compost/biochar amendments, the improvement of soil fertility was  
405 followed by an increase in biomass production of maize (Abbas et al., 2020; Manolikaki and  
406 Diamadopoulou, 2019; Zahra et al., 2021), *Salix purpurea* (Seehausen et al., 2017), lettuce (Trupiano et  
407 al., 2017), and *Phragmites karka* (Abideen et al., 2020). The importance of N in this growth amelioration  
408 was confirmed by the decrease in C/N ratio (T1) and the increase in N/P ratio in the plants, demonstrating  
409 a reduction of N limitation under amended conditions (Cao and Chen, 2017), and a change of the system  
410 from a N limitation towards a more equilibrated system, in terms of plant nutrition.

411 Except for the available P, nutrient availability was mainly dependent on the compost content,  
412 as higher values were found in the compost only treatment and diminished with the proportion of  
413 compost, which could be explained by the fact that compost contains more nutrients, which are more  
414 available. On the contrary, P availability was more important in the mixture with higher proportion of  
415 biochar. Wood biochar seems to have the potential to raise P availability through a direct addition,  
416 through a pH raise of soil or by inducing a competition with organic anions brought by biochar on soil  
417 fixation site (Houben et al., 2017). However, our results reject the first explanation as pH changes were  
418 not significant. Moreover, compost had a slightly higher P content than biochar, and thus a competition  
419 with other anions seems more likely. Altogether, soil parameters show that compost and biochar have  
420 no synergistic effect on soil but rather an additional effect.

421

#### 422 **4.2. The ratio BC30CP70 is the best plant growth improver, in a synergistic interaction** 423 **between biochar and compost**

424 Interestingly, the soil analysis revealed that N availability was dependent on the ratio of compost  
425 and biochar, and the highest availability of N (ammonium-N + nitrate-N) was found for the ratio  
426 BC50CP50, while N chemical fertilisation further increased N availability. From this, we could thus  
427 hypothesise that the highest growth and uptake of N would occur in this treatment. However, the best  
428 growth was measured for the ratio BC30CP70, which showed even higher biomass production than the  
429 N fertilisation treatment (CT/Fert+). In addition, compared to the other treatments, including chemical  
430 N fertiliser, this biochar/compost ratio still increased plant growth at the successive harvests. It also  
431 induced an increase in N/P ratio in the plants, and thus a reduction in N limitation, after 13 weeks,

432 indicating a longer lasting effect. Thus, this study demonstrated that a ratio of 30 % biochar and 70 %  
433 compost allowed for synergistic interactions between those two amendments to increase nutrient uptake  
434 by plants, although the synergism was not observed in terms of nutrient availability in the soil. This  
435 could be related to the high amount of carbon and nutrients added through compost and their stabilisation  
436 via a small dose of biochar, and a modification of plant physiological state in response to the change in  
437 soil growing conditions (Kidd et al., 2009). This biochar/compost ratio also improved growth under N  
438 fertilisation more than for the other treatments. Finally, as the ratio BC30CP70 showed the best results,  
439 higher than the fertilised control, we can conclude that adding a mixture of biochar and compost at such  
440 a ratio could reduce mineral N fertilisation or be combined to it to further improve its effect. Biochar  
441 and compost used together as soil amendment are extensively studied but few works address the ratio  
442 differences of such mixtures and their potentialities in terms of soil functioning and plant development.  
443 Such practice needs, however, to be evaluated in terms of cost/benefits for the farmer. Our results agree  
444 with our previous study showing that this specific ratio (BC30CP70) was able to substitute for P and K  
445 fertilisation for the same soil, under field conditions (Nobile et al., 2022). Taken together, we suggest  
446 that biochar-compost mixtures at the ratio 30 % - 70 % have potential to reduce the regular N, P and  
447 K fertilisation, although more testing is needed, using different types of biochar and compost and NPK  
448 fertilisers under contrasting pedoclimatic conditions and cropping systems.

449

## 450 **5. Conclusion**

451 A pot experiment was performed to evaluate the influence of the biochar/compost ratio in  
452 amendment mixtures with regards to their effects on soil fertility and plant growth. This study confirmed  
453 our two hypotheses: (i) biochar and compost association gave better outcomes than their single  
454 applications in terms of plant growth and nutrient availability, and (ii) the effect of biochar/compost  
455 mixtures depends on their ratio and nitrogen fertilisation. Altogether, the results showed that  
456 associating biochar and compost can have synergistic effects and may be able to alleviate chemical N  
457 fertilisation if used in an appropriate ratio. We therefore suggest adding a small amount of biochar to  
458 compost before field application could be useful to reduce mineral fertiliser input. This may lead to  
459 better outcomes in terms of plant growth and carbon storage than compost application alone. Such  
460 synergism between different biochar and compost types remains to be elucidated.

461

## 462 **Declarations**

463 **Funding.** The project (FUI Biochar) was funded by Bpifrance and the Région Hauts-de-France.

464 **Competing interests.** The authors declare that they have no competing interests.

465 **Ethics Approval.** Not applicable.

466 **Consent.** Not applicable.

467 **Data availability.** The data will be made available by the corresponding authors on reasonable request.

468

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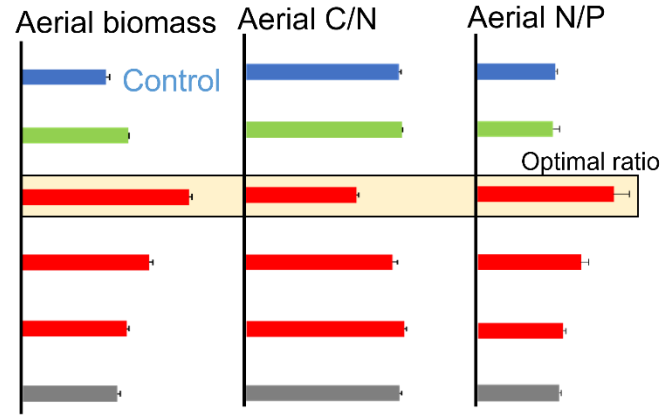
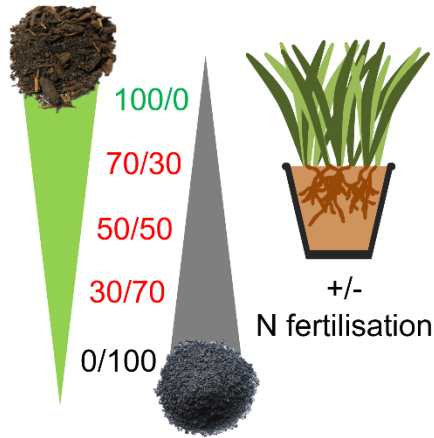
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654 **Graphical Abstract**

Mixtures ratios  
Compost x Biochar



Synergistic effect  
From N limitation to equilibrated system

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Table 1. Initial properties of the soil and amendment used in the experimentation

	Units (dry weight)	Soil	Compost	Biochar
Clay	%	20.5	-	-
Fine silt	%	26.4	-	-
Coarse silt	%	43.0	-	-
Fine sand	%	7.47	-	-
Coarse sand	%	2.60	-	-
pH (H <sub>2</sub> O) <sup>a</sup>	-	7.93	8.00	11.4
Total carbonates <sup>b</sup>	%	0.80	-	-
Organic carbon <sup>c</sup>	g.kg <sup>-1</sup>	10.2	292	316
Cation exchange capacity <sup>d</sup>	cmolc.kg <sup>-1</sup>	109	34.9	8.50
Total nitrogen <sup>e</sup>	g.kg <sup>-1</sup>	1.13	27.0	0.84
Total phosphorus	g.kg <sup>-1</sup>	0.57	4.20	3.71
Total potassium	g.kg <sup>-1</sup>	14.3	17.0	17.9
Total magnesium	g.kg <sup>-1</sup>	3.20	2.80	5.07
Total calcium	g.kg <sup>-1</sup>	7.77	29.0	34.0
Total sodium	g.kg <sup>-1</sup>	5.85	-	-

a 1:5 ratio NF ISO 10390, b NF ISO 10693, c dry combustion NF ISO 14235, d Metson method NFX 31-130, e Dumas method.

Data from Nobile et al. (2022).

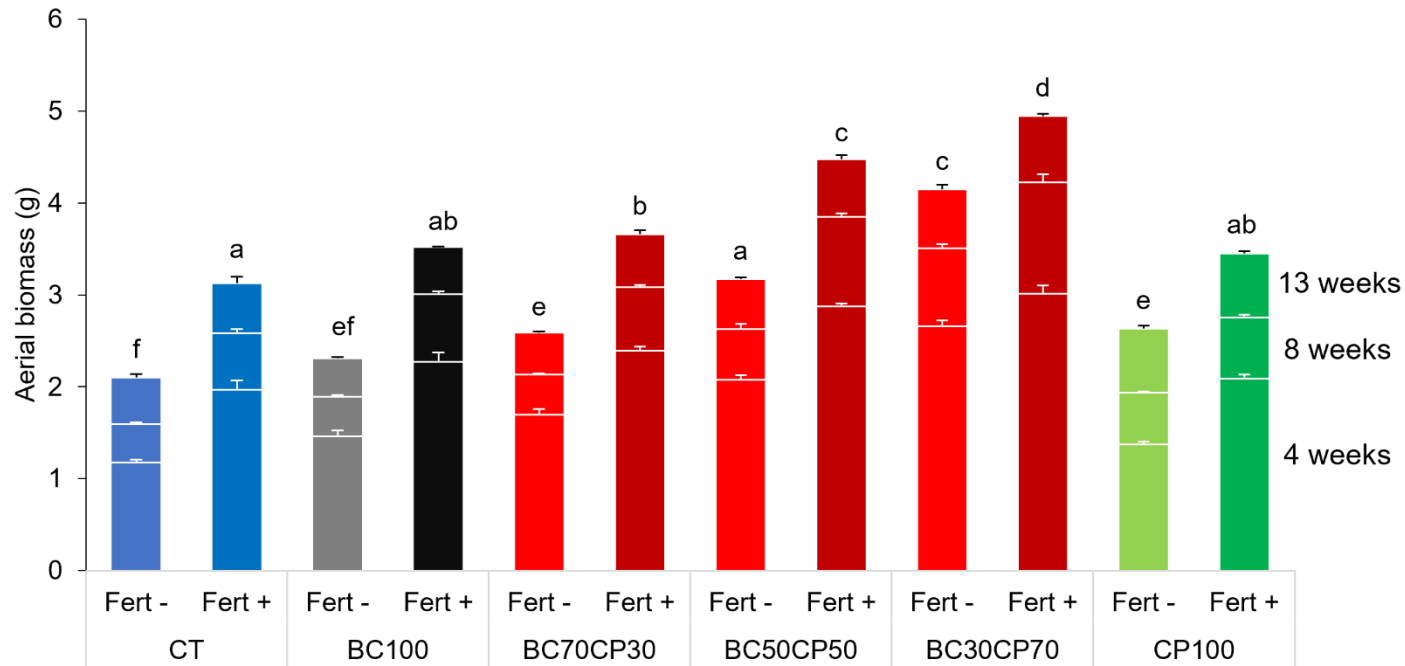
Table 2. Chemical properties of the different substrates at the beginning of the experiment. CT = non-amended soil, BC100 = soil amended with biochar, BC70CP30 = soil amended with a biochar:compost mixture in the ratio 70:30 (on a dry weight basis); BC50CP50 = soil amended with a biochar:compost mixture in the ratio 50:50 (on a dry weight basis); BC30CP70 = soil amended with a biochar:compost mixture in the ratio 70:30 (on a dry weight basis); CP100 = soil amended with compost. All amendments were added at a dose of 10 t.ha<sup>-1</sup> in total. Fert - = no application of a nitrogen fertilization; Fert + = application of a nitrogen fertilization. Letters indicate a significant difference ( $p < 0.05$ ) ( $n = 3$ ).

Amendment	Fertilization	pH <sub>KCl</sub>	Total nitrogen (g.kg <sup>-1</sup> )	Ammonium-N (mg.kg <sup>-1</sup> )	Nitrate-N (mg.kg <sup>-1</sup> )	Organic carbon (g.kg <sup>-1</sup> )	C/N	Available [P] (g.kg <sup>-1</sup> )	Available [K] (g.kg <sup>-1</sup> )	Available [Mg] (mg.kg <sup>-1</sup> )	Available [Ca] (mg.kg <sup>-1</sup> )
CT	Fert -	7.51 ± 0.04 bcde	1.1 ± 0.0 c	2.70 ± 0.43 ab	13 ± 8 f	10.31 ± 0.04 bc	9.59 ± 0.23 ac	77 ± 8 def	147 ± 4 f	84 ± 2 e	4081 ± 239 a
	Fert +	7.49 ± 0.01 de	1.1 ± 0.1 bc	1.26 ± 0.32 c	54 ± 4 cd	9.89 ± 0.39 c	8.66 ± 0.32 c	64 ± 4 f	125 ± 10 f	82 ± 4 e	3930 ± 65 a
BC100	Fert -	7.57 ± 0.00 a	1.3 ± 0.0 ab	1.26 ± 0.10 c	44 ± 4 de	16.18 ± 1.53 a	12.22 ± 1.04 b	109 ± 3 a	186 ± 3 d	94 ± 1 d	4294 ± 130 a
	Fert +	7.57 ± 0.01 ab	1.3 ± 0.0 ab	1.75 ± 0.20 bc	65 ± 3 bcd	14.59 ± 0.13 a	11.03 ± 0.10 ab	105 ± 1 ab	188 ± 1 de	96 ± 1 d	4402 ± 42 a
BC70CP30	Fert -	7.57 ± 0.01 ab	1.4 ± 0.0 a	1.95 ± 0.14 abc	55 ± 3 cd	14.65 ± 0.65 a	10.82 ± 0.34 ab	102 ± 2 abc	203 ± 1 cde	102 ± 1 bcd	4174 ± 79 a
	Fert +	7.52 ± 0.02 cde	1.4 ± 0.0 a	2.07 ± 0.07 abc	79 ± 1 b	14.24 ± 0.70 a	10.53 ± 0.20 ab	99 ± 4 abc	199 ± 4 cde	101 ± 1 cd	4179 ± 45 a
BC50CP50	Fert -	7.52 ± 0.00 cde	1.3 ± 0.0 ab	1.39 ± 0.09 c	72 ± 5 bc	13.15 ± 0.56 abc	10.16 ± 0.26 ac	86 ± 4 cde	191 ± 7 cde	103 ± 2 bcd	4259 ± 141 a
	Fert +	7.48 ± 0.02 e	1.4 ± 0.0 a	1.94 ± 0.17 abc	119 ± 3 a	13.81 ± 0.52 a	10.08 ± 0.15 ac	91 ± 1 bcd	199 ± 1 cde	107 ± 2 abc	4388 ± 193 a
BC30CP70	Fert -	7.54 ± 0.00 abcd	1.3 ± 0.1 ab	2.88 ± 0.11 ab	22 ± 1 ef	13.52 ± 0.88 ab	10.10 ± 0.22 ac	76 ± 4 def	213 ± 9 bcd	102 ± 2 bcd	4032 ± 77 a
	Fert +	7.54 ± 0.01 abcd	1.4 ± 0.1 a	2.33 ± 0.41 abc	54 ± 2 cd	14.63 ± 0.67 a	10.60 ± 0.20 ab	77 ± 2 def	217 ± 4 bc	104 ± 1 bcd	4316 ± 149 a
CP100	Fert -	7.53 ± 0.01 abcde	1.5 ± 0.0 a	2.82 ± 0.28 ab	31 ± 6 ef	14.15 ± 0.43 a	9.60 ± 0.05 ac	77 ± 1 def	244 ± 5 a	114 ± 2 a	4167 ± 120 a
	Fert +	7.56 ± 0.02 abc	1.5 ± 0.0 a	3.15 ± 0.31 a	64 ± 5 bcd	14.41 ± 0.05 a	9.72 ± 0.15 ac	73 ± 1 ef	234 ± 3 ab	111 ± 1 ab	4306 ± 73 a

Table 3. Chemical properties of the different substrates at the end of the experiment. CT = non-amended soil, BC100 = soil amended with 10 t.ha<sup>-1</sup> of biochar, BC70CP30 = soil amended with 10 t.ha<sup>-1</sup> of a biochar:compost mixture in the ratio 70:30 (on a dry weight basis); BC50CP50 = soil amended with 10 t.ha<sup>-1</sup> of a biochar:compost mixture in the ratio 50:50 (on a dry weight basis); BC30CP70 = soil amended

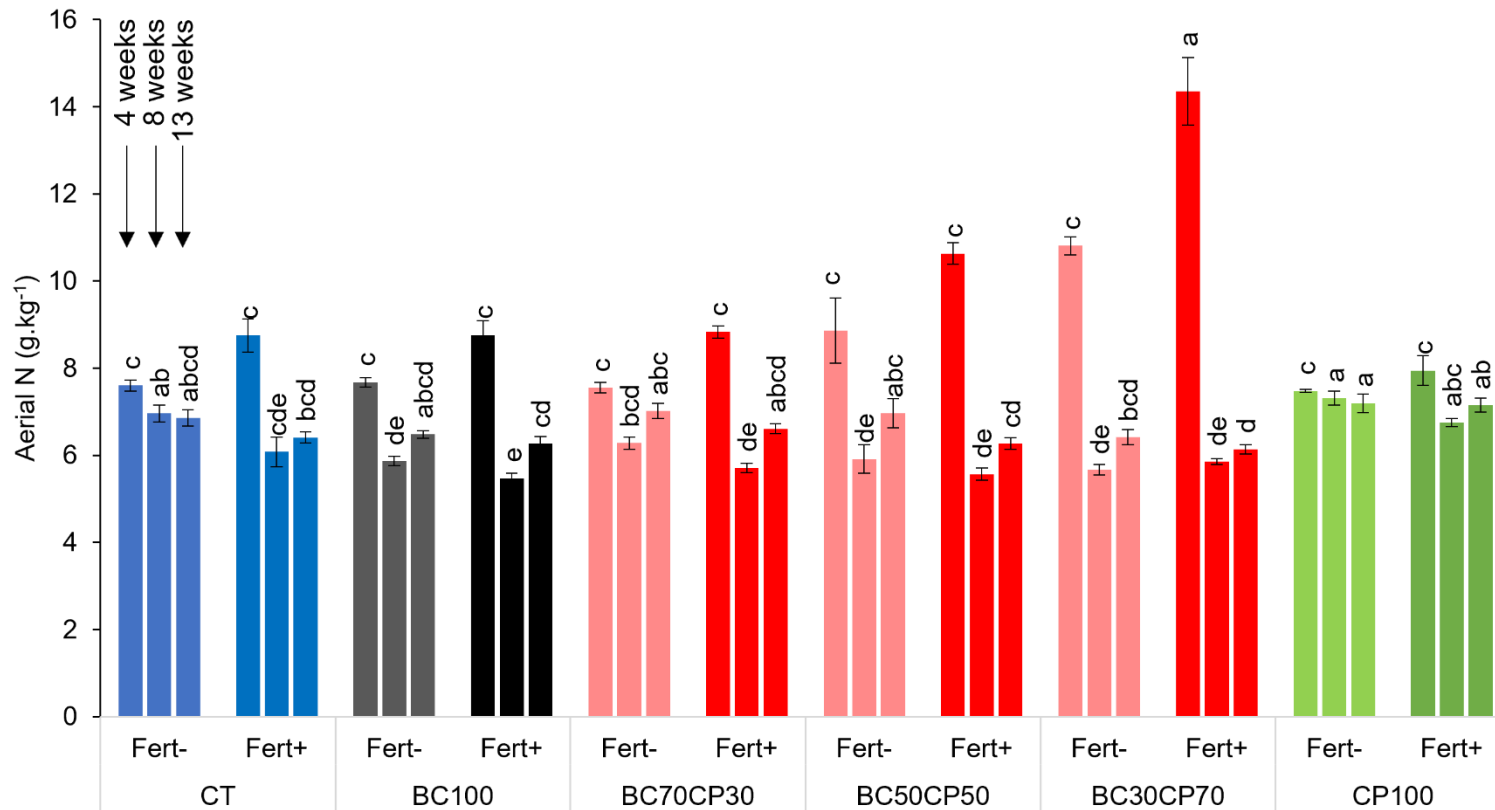
with 10 t.ha<sup>-1</sup> of a biochar:compost mixture in the ratio 70:30 (on a dry weight basis); CP100 = soil amended with 10 t.ha<sup>-1</sup> of compost. Fert - = no application of a nitrogen fertilization; Fert + = application of a nitrogen fertilization. Letters indicate significant difference between treatments ( $p < 0.05$ ) ( $n = 5$ ).

Amendment	Fertilization	pH <sub>KCl</sub>	Total nitrogen (g.kg <sup>-1</sup> )	Ammonium-N (mg.kg <sup>-1</sup> )	Nitrate-N (mg.kg <sup>-1</sup> )	Organic carbon (g.kg <sup>-1</sup> )	C/N	Available [P] (g.kg <sup>-1</sup> )	Available [K] (g.kg <sup>-1</sup> )	Available [Mg] (mg.kg <sup>-1</sup> )	Available [Ca] (mg.kg <sup>-1</sup> )
CT	Fert -	7.48 ± 0.04 a	1.3 ± 0.0 de	1.43 ± 0.23 abc	0.25 ± 0.04 ab	10.8 ± 0.4 bc	8.35 ± 0.27 cd	62 ± 1 fg	108 ± 2 g	74 ± 3 e	3246 ± 41 d
	Fert +	7.48 ± 0.04 a	1.3 ± 0.0 e	0.90 ± 0.16 cd	0.18 ± 0.01 ab	10.4 ± 0.3 c	8.10 ± 0.15 d	53 ± 1 g	92 ± 2 h	72 ± 2 e	3334 ± 43 cd
BC100	Fert -	7.56 ± 0.03 a	1.4 ± 0.0 cde	0.84 ± 0.11 d	0.24 ± 0.03 ab	14.3 ± 0.6 a	10.05 ± 0.22 ab	114 ± 3 a	148 ± 2 ab	90 ± 0 b	3640 ± 48 abc
	Fert +	7.58 ± 0.02 a	1.4 ± 0.0 cde	0.87 ± 0.08 d	0.23 ± 0.02 ab	14.6 ± 0.8 a	10.29 ± 0.30 a	103 ± 3 b	128 ± 2 cde	90 ± 0 b	3688 ± 44 a
BC70CP30	Fert -	7.58 ± 0.02 a	1.4 ± 0.0 cde	1.10 ± 0.09 bcd	0.18 ± 0.02 ab	13.9 ± 0.5 a	9.79 ± 0.32 abc	94 ± 4 bc	140 ± 5 bc	94 ± 3 b	3674 ± 94 ab
	Fert +	7.56 ± 0.03 a	1.5 ± 0.0 abc	1.29 ± 0.06 abcd	0.26 ± 0.03 ab	14.7 ± 0.7 a	9.66 ± 0.28 abcd	94 ± 2 bc	124 ± 3 def	92 ± 2 b	3526 ± 56 abcd
BC50CP50	Fert -	7.54 ± 0.04 a	1.5 ± 0.0 abc	1.06 ± 0.08 cd	0.24 ± 0.03 ab	13.5 ± 0.5 ab	9.01 ± 0.11 abcd	86 ± 2 cde	134 ± 3 bcde	90 ± 0 b	3486 ± 56 abcd
	Fert +	7.52 ± 0.07 a	1.4 ± 0.0 bcde	0.99 ± 0.10 cd	0.16 ± 0.01 b	13.8 ± 0.7 ab	9.55 ± 0.34 abcd	92 ± 3 cd	112 ± 2 fg	90 ± 0 b	3466 ± 58 abcd
BC30CP70	Fert -	7.50 ± 0.04 a	1.5 ± 0.0 abc	0.96 ± 0.12 cd	0.25 ± 0.02 ab	14.9 ± 1.5 a	9.79 ± 1.03 abc	79 ± 1 e	120 ± 4 efg	120 ± 4 a	3446 ± 94 abcd
	Fert +	7.50 ± 0.06 a	1.5 ± 0.0 abcd	0.75 ± 0.08 d	0.24 ± 0.01 ab	13.2 ± 0.6 abc	8.90 ± 0.17 abcd	83 ± 2 de	108 ± 6 g	108 ± 2 a	3368 ± 20 bcd
CP100	Fert -	7.58 ± 0.02 a	1.7 ± 0.0 a	1.78 ± 0.19 a	0.24 ± 0.03 ab	14.8 ± 0.5 a	8.63 ± 0.17 bcd	69 ± 1 f	156 ± 4 a	156 ± 4 c	3584 ± 121 abc
	Fert +	7.54 ± 0.03 a	1.6 ± 0.0 ab	1.66 ± 0.13 ab	0.28 ± 0.03 a	14.4 ± 0.6 a	8.90 ± 0.17 abcd	65 ± 2 f	136 ± 6 bcd	136 ± 6 d	3410 ± 106 abcd



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669 Figure 1. Plant aerial biomass (g) measured in the aerial tissue of *Lolium multiflorum* after 4 weeks (bottom), 8 weeks (middle), 13 weeks (top) of growth and  
 670 total aerial biomass produced during the experiment (full bar) on the different substrates. CT = non-amended soil, BC100 = soil amended with 10 t.ha<sup>-1</sup> of  
 671 biochar, BC70CP30 = soil amended with 10 t.ha<sup>-1</sup> of a biochar:compost mixture in the ratio 70:30 (on a dry weight basis); BC50CP50 = soil amended with 10  
 672 t.ha<sup>-1</sup> of a biochar:compost mixture in the ratio 50:50 (on a dry weight basis); BC30CP70 = soil amended with 10 t.ha<sup>-1</sup> of a biochar:compost mixture in the ratio  
 673 70:30 (on a dry weight basis); CP100 = soil amended with 10 t.ha<sup>-1</sup> of compost. Fert - = no application of a nitrogen fertilization; Fert + = application of a  
 674 nitrogen fertilization. Letters indicate a significant difference ( $p < 0.05$ ) ( $n = 5$ )  
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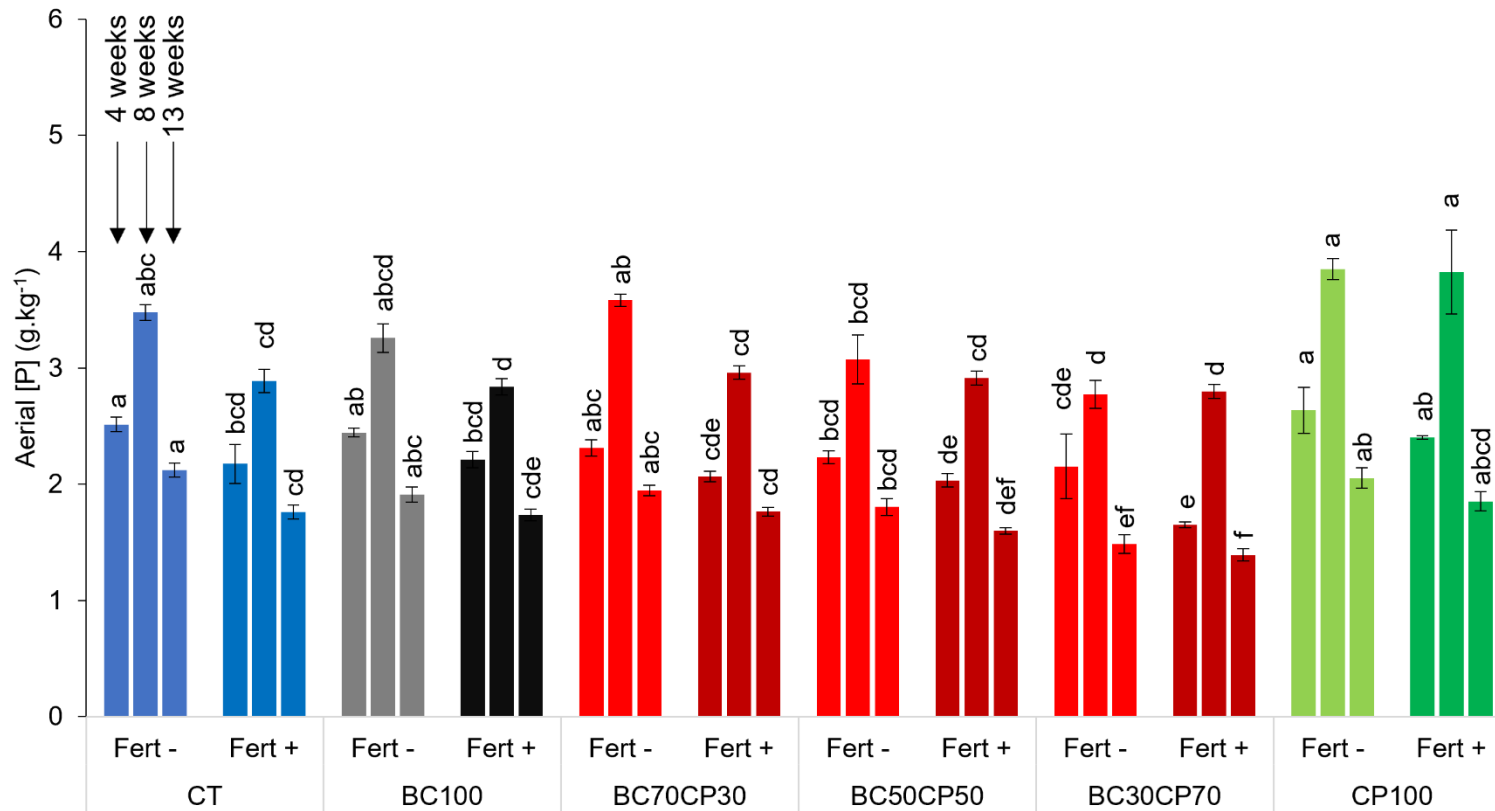
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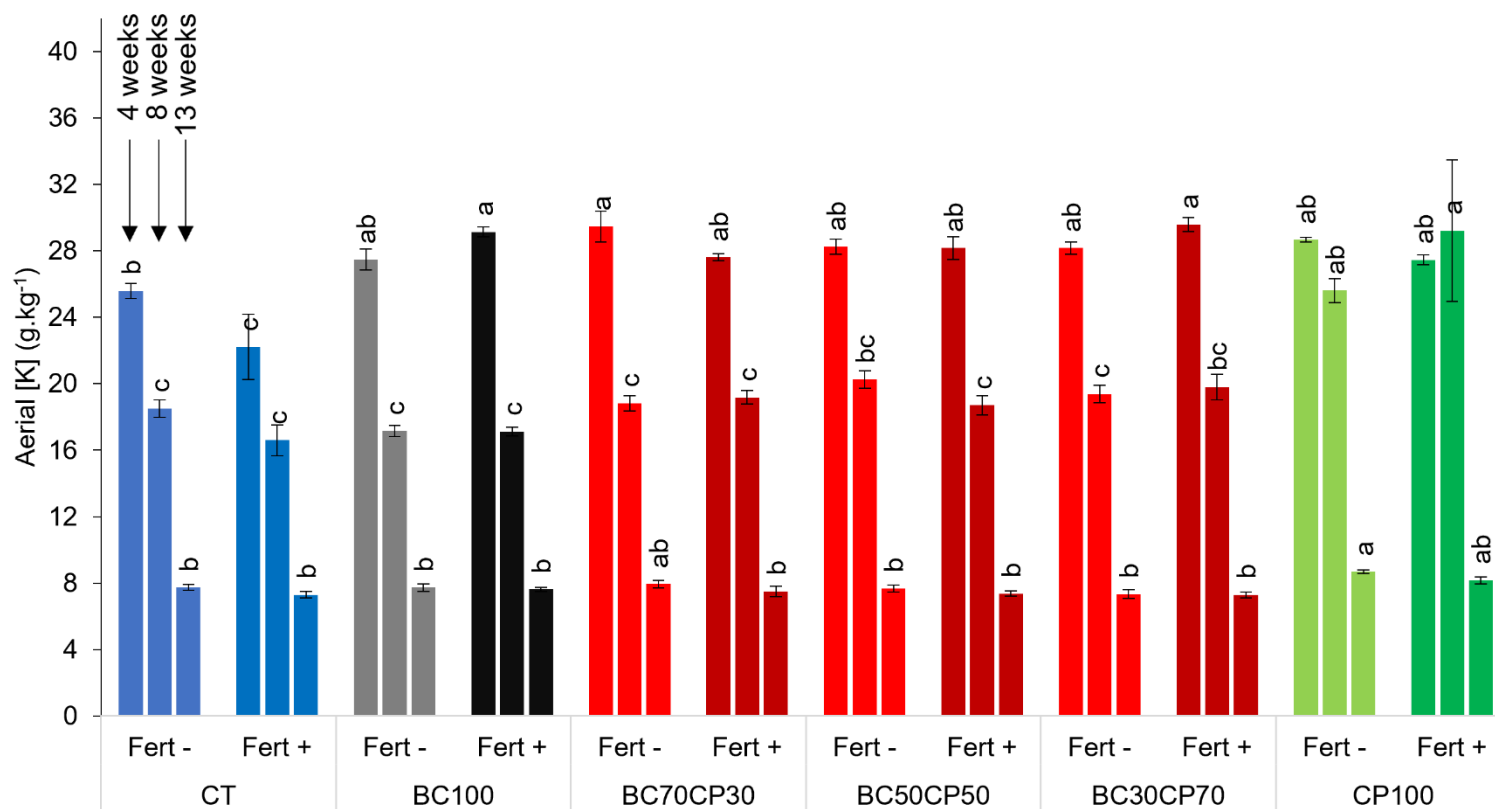
Figure 2. Nitrogen content (g.kg<sup>-1</sup>) measured after 4 weeks (left), 8 weeks (middle) and 13 weeks (right) of growth on the different substrates in the aerial of *Lolium multiflorum*. CT = non-amended soil, BC100 = soil amended with biochar, BC70CP30 = soil amended with a biochar:compost mixture in the ratio 70:30 (on a dry weight basis); BC50CP50 = soil amended with a biochar:compost mixture in the ratio 50:50 (on a dry weight basis); BC30CP70 = soil amended with a biochar:compost mixture in the ratio 70:30 (on a dry weight basis); CP100 = soil amended with compost. All amendments were added at a dose of 10 t.ha<sup>-1</sup> total. Fert - = no application of a nitrogen fertilization; Fert + = application of a nitrogen fertilization. Letters indicate a significant difference for each week (p < 0.05) (n = 5)





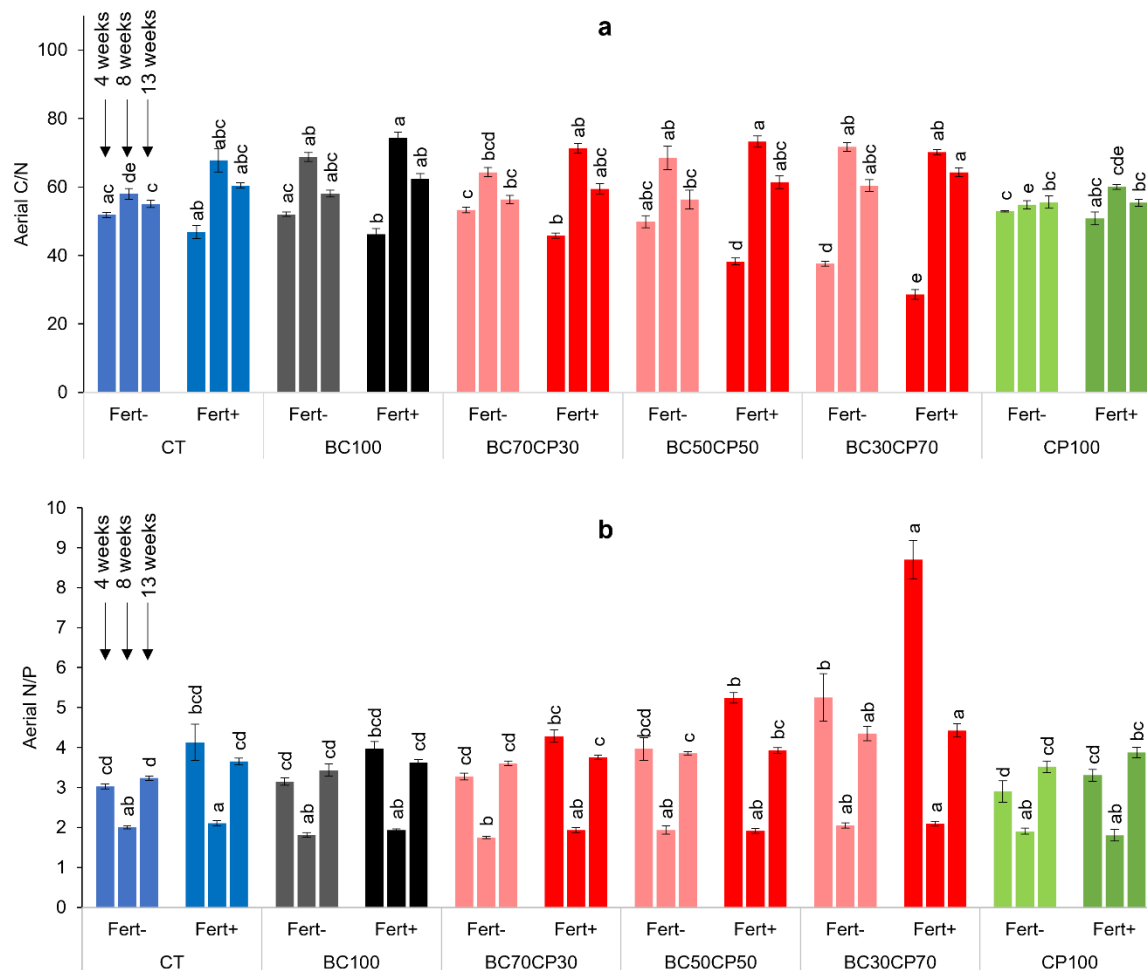
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684 Figure 3. Phosphorus content (g.kg<sup>-1</sup>) measured after 4 weeks (left), 8 weeks (middle) and 13 weeks (right) of growth on the different substrates in the aerial  
 685 tissues of *Lolium multiflorum*. CT = non-amended soil, BC100 = soil amended with biochar, BC70CP30 = soil amended with a biochar:compost mixture in the  
 686 ratio 70:30 (on a dry weight basis); BC50CP50 = soil amended with a biochar:compost mixture in the ratio 50:50 (on a dry weight basis); BC30CP70 = soil  
 687 amended with a biochar:compost mixture in the ratio 70:30 (on a dry weight basis); CP100 = soil amended with compost. All amendments were added at a dose  
 688 of 10 t.ha<sup>-1</sup> total. Fert - = no application of a nitrogen fertilization; Fert + = application of a nitrogen fertilization. Letters indicate a significant difference for  
 689 each week ( $p < 0.05$ ) ( $n = 5$ )  
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692 Figure 4. Potassium content (g.kg<sup>-1</sup>) measured after 4 weeks (left), 8 weeks (middle) and 13 weeks (right) of growth on the different substrates in the aerial  
 693 tissues of *Lolium multiflorum*. CT = non-amended soil, BC100 = soil amended with biochar, BC70CP30 = soil amended with a biochar:compost mixture in the  
 694 ratio 70:30 (on a dry weight basis); BC50CP50 = soil amended with a biochar:compost mixture in the ratio 50:50 (on a dry weight basis); BC30CP70 = soil  
 695 amended with a biochar:compost mixture in the ratio 70:30 (on a dry weight basis); CP100 = soil amended with compost. All amendments were added at a dose  
 696 of 10 t.ha<sup>-1</sup> total. Fert - = no application of a nitrogen fertilization; Fert + = application of a nitrogen fertilization. Letters indicate a significant difference for  
 697 each week (p < 0.05) (n = 5)  
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700 Figure 5. C/N ratio (a) and N/P ratio (b) measured after 4 weeks (left), 8 weeks (middle) and 13 weeks (right) of growth on the different substrates in the aerial  
 701 tissues of *Lolium multiflorum*. CT = non-amended soil, BC100 = soil amended with biochar, BC70CP30 = soil amended with a biochar:compost mixture in the  
 702 ratio 70:30 (on a dry weight basis); BC50CP50 = soil amended with a biochar:compost mixture in the ratio 50:50 (on a dry weight basis); BC30CP70 = soil  
 703 amended with a biochar:compost mixture in the ratio 70:30 (on a dry weight basis); CP100 = soil amended with compost. All amendments were added at a dose  
 704 of 10 t.ha<sup>-1</sup> total. Fert - = no application of a nitrogen fertilization; Fert + = application of a nitrogen fertilization. Letters indicate a significant difference for  
 705 each week ( $p < 0.05$ ) ( $n = 5$ ).

