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1 **Effects of gasification biochar on plant-available water capacity and plant growth in two contrasting**
2 **soil types**

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15

16 **Abstract**

17 Gasification biochar (GB) contains recalcitrant carbon that can contribute to soil carbon sequestration
18 and soil quality improvement. However, the impact of GB on plant-available water capacity (AWC)
19 and plant growth in diverse soil types still needs to be explored.

20 A pot experiment with spring barley (*Hordeum vulgare* L.) was conducted to investigate the effect of
21 soil amendment by 1 % straw and wood gasification biochar (SGB and WGB), respectively, on AWC
22 and plant growth responses under two levels of water supply in a temperate sandy loam and a coarse
23 sandy subsoil. In the sandy loam, the reduced water regime significantly affected plant growth and
24 water consumption, whereas the effect was less pronounced in the coarse sand. Irrespective of the
25 soil type, both GBs increased AWC by 17-42%, with the highest absolute effect in the coarse sand. The
26 addition of SGB to coarse sand led to a substantial increase in plant biomass under both water
27 regimes: shoot growth by 40-165% and root growth by 50-57%. However, no positive effects were
28 achieved by the addition of WGB. In the sandy loam, soil application of GB had no or negative effects
29 on plant growth.

30 Our results suggest that SGB has considerable potential for enhancing crop productivity in coarse
31 sandy soils by increasing soil water retention and improving root development.

32

33 **Keywords:**

34 Gasification biochar; Available water capacity; Coarse sand; Barley; Shoot and root growth; Soil
35 structure

36

37 **Abbreviations**

38 GB Gasification biochar

39 SGB Straw gasification biochar

40 WGB Wood gasification biochar

41 AWC Plant-available water capacity

42 WHC Water holding capacity

43

44 **1. Introduction**

45 An improvement in soil quality and an increase in soil organic matter reduce the exposure and
46 vulnerability of crops to extreme events such as drought (Altieri et al., 2015). The annual soil
47 application of agriculture residues is one of the management tools available for increasing soil organic
48 matter content (Reeves, 1997). However, at the same time the demand for biomass for bioenergy
49 production is growing, putting even more pressure on plant production and the utilization of
50 agriculture and forestry residues (Powlson et al., 2011). Thermal gasification of these residues not
51 only produces sustainable bioenergy (Ahrenfeldt et al., 2013), but also a by-product, gasification
52 biochar (GB), a potentially valuable soil amendment (Müller-Stöver et al., 2012). Depending on the
53 feedstock and specific thermal technology used, GB may contain up to 60% carbon, which has been
54 shown to be stable towards microbial degradation after soil application and may stay in the soil
55 carbon pool for decades (Hansen et al., 2015). Soil application of GB has the potential to increase the
56 soil organic carbon content, thereby having a beneficial impact on climate change mitigation and soil
57 quality (Sohi et al., 2010).

58 However, very little research has been undertaken so far on the effect of GB soil amendment on
59 physical soil properties and plant growth. The majority of studies available have been conducted with
60 pyrolysis biochar, the main product of a pyrolysis process conducted under low-oxygen conditions at
61 temperatures of between 400-750°C (Kammann et al., 2011; Baronti et al., 2014; Abel et al., 2013).
62 Pyrolysis biochar typically contains 50-80% carbon, often including a labile carbon fraction that can
63 stimulate microbial activity influencing initial mineralization processes (Bruun et al., 2011). On the
64 other hand, GB is produced at higher temperatures (700-1200°C), resulting in a by-product with a

65 lower C content (20–60%) but higher stability towards microbial degradation (Müller-Stöver et al.,
66 2012; Bruun et al., 2014; Hansen et al., 2015).

67 Biochar has a significant adsorbing ability due to its high specific surface area, and its internal porosity
68 may contribute to increasing the water holding capacity (WHC) (Uzoma et al., 2011; Kammann et al.,
69 2011; Bruun et al., 2014) and plant-available water capacity of soil (AWC) (Abel et al., 2013). Especially
70 coarse sandy soils have poor water and nutrient retention, resulting in a risk of drought in dry periods
71 and nutrient losses in wet periods. Hence, large proportions of hydrophilic micropores (0.2 – 30 µm)
72 in biochar, potentially retaining plant-available water, may have the ability to improve AWC in coarse
73 sandy soils (Hardie et al., 2014). Furthermore, decrease in soil bulk density is often reported after
74 biochar application (Rogovska et al., 2014) along with an increase in total porosity (Abel et al., 2013),
75 which may improve the soil structure, resulting in better water retention (Sun and Lu, 2014) and
76 improved root growth (Bruun et al., 2014). Thus, improvement of AWC in biochar-amended soil is
77 apparently not straightforward, but rather a combination of several factors such as soil type, biochar
78 amendment rate and biochar properties (Barnes et al., 2014). In a vineyard field experiment, Baronti
79 et al. (2014) reported that biochar application increased the available water content and leaf water
80 potential during dry periods. In contrast, Jeffery et al. (2015) found that biochar had no effect on soil
81 water retention, which they attribute to the hydrophobicity of the biochar used. Similarly, Hardie et
82 al. (2014) found that acacia biochar had no effect on plant-available water capacity in a sandy loam
83 soil, partly due to the high natural variation in soil physical properties. Biochar amendment has also
84 shown the ability to increase plant root and shoot growth and drought tolerance without increasing
85 soil water availability, improving plant ecophysiological responses related to water status such as leaf

86 osmotic potential, stomata resistance and water use efficiency (Kammann et al., 2011; Haider et al.,
87 2014).

88 An improvement in soil structure may be especially beneficial in coarse sandy soils showing high
89 mechanical resistance to root growth due to low compressibility and high friction (Bruun et al., 2014).
90 Rooting depths of only 50-70 cm are reported in soils with coarse sandy subsoil, while in loamy soils
91 located under the same climatic growing conditions roots may reach depths of >140 cm (Madsen,
92 1985). Consequently, the yield potentials of crops can generally not be fully exploited in coarse sandy
93 soils. However, the particle size and pore structure of the specific biochar material may play a
94 significant role when aiming for soil structure improvement (Abel et al., 2013; Sun and Lu, 2014).

95 Further information about the effects of specific GBs on the properties of different soil types as well
96 as on plant growth under drought stress is required to learn more about how to optimize the use of a
97 limited amount of GB material to improve soil quality and increase crop yields. The overall aim of this
98 study was therefore to evaluate the effects of two contrasting GB materials on the capacity of plant-
99 available water (AWC) and plant growth responses (shoot and root biomass, leaf water potential,
100 stomatal conductance and carbon isotope discrimination) of spring barley (*Hordeum vulgare* L.) grown
101 in two different soil types under sufficient and reduced water supply.

102

103

104 **2. Materials and methods**

105 *2.1. Biochar*

106 Two biochar materials were used in this study: wood gasification biochar (WGB) and straw gasification
107 biochar (SGB). SGB was produced in a Low Temperature Circulating Fluidized Bed gasifier (LT-CFB) at
108 750°C using winter wheat (*Triticum aestivum* L.) as a feedstock. WGB was produced in a TwoStage
109 gasifier at 1200°C from pine wood (*Pinus spp.*) (Ahrenfeldt et al., 2013). A number of physicochemical
110 characteristics were determined for the GB produced and are shown in Table 1 and 2. The total
111 content of organic C was measured on an elemental analyzer (FLASH 2000 Organic Elemental
112 Analyzer, Thermo Scientific, Cambridge UK). The elemental composition was determined by ICP-OES
113 after acid digestion (ISO 11885). The specific surface area was determined by the Brunauer-Emmett-
114 Teller (BET) method by nitrogen gas sorption at 77 K (Quantachrome instruments, Boynton Beach,
115 USA). The pH of the biochar was measured in a 1:5 (w/v) biochar/Milli-Q water suspension by using a
116 pH meter (Mettler-Toledo AG, Switzerland). More details about the production processes, analytical
117 methods and further characteristics of both SGB and WGB can be found in Hansen et al. (2015).

118 Table 1 here.

119 Table 2 here.

120

121 *2.2. Soils*

122 The soils used in this study were sandy loam and sandy soils (USDA textural classification). The sandy
123 loam soil was collected from the Ap horizon (0-25 cm) of a conventional agricultural field on the

124 Bregentved Estate in Zealand, Denmark (55° 22' N, 12° 05' E). The sandy soil was collected on the
125 Jyndevad Research Station of Aarhus University, Denmark (54° 53' N, 9° 07' E) from the B horizon (25-
126 100 cm depth) and is further termed coarse sandy soil. Both soils were air-dried and sieved to obtain
127 a fraction ≤ 2 mm. The soil properties are shown in Table 3.

128 Table 3 here

129

130 *2.3. Experiment setup*

131 The experiment was conducted in the Risø Environmental Risk Assessment Facility (RERAF) phytotron
132 at the Technical University of Denmark, Roskilde campus, Denmark. The experiment involved 12
133 treatments with four replicates: two soil types, three GB amendments (control without GB, 1% WGB
134 and 1% SGB respectively) and two water regimes (70% and 30% of the water-holding capacity (WHC)
135 of the control treatment respectively). It was decided to base the water supply on the WHC of the
136 control treatment to avoid effects simply caused by a higher water supply to the biochar-amended
137 pots. The WHC was determined for each soil type in 28 cm-high PVC pots with an inner diameter of 10
138 cm, equipped with a wick system at the bottom allowing drainage preventing eventual excessive
139 accumulation of water near the lower boundary (Fig. 1). To determine WHC, the sandy loam soil was
140 packed into the pots using pressure of a metal piston of the same diameter as the pot, which resulted
141 in a bulk density of 1.47 g cm^{-3} in the control treatment. The coarse sandy soil was added to the pot
142 without pressure and had a bulk density of 1.63 g cm^{-3} in the control treatment. The pots with soil
143 were submersed in water for 24 hours following a subsequent drainage period of 24 hours while

144 preventing evaporation. The recorded weight of the water held in the soil after drainage was taken as
145 WHC.

146 Prior to the experiment, the dry soil was weighed into plastic bags to give 2.6 kg of sandy loam soil
147 and 3 kg of coarse sandy soil respectively. Nutrients were added in a liquid solution to the soil in each
148 bag at a rate of 60 mg P, 40 mg Mg, 124 mg S, 166 mg K, 3.4 mg Mn, 1.2 mg Zn, 0.2 mg Cu and 0.1 mg
149 Mo kg⁻¹ soil (as KH₂PO₄, MgSO₄, K₂SO₄, MnSO₄, ZnSO₄, CuSO₄, Na₂MoO₄). The soil was thoroughly
150 mixed with 1% of the GB material on a dry weight basis. The WGB was sieved to obtain a fraction < 1
151 cm. The mixtures and control treatments were packed with the same pressure as for the WHC
152 determination, respectively. With these densities, 1% of GB corresponds to approximately 36 t ha⁻¹ in
153 a sandy loam soil and approximately 40 t ha⁻¹ in a coarse sandy soil, if incorporated to 25 cm soil
154 depth.

155 Prior to the experiment, the conditions in the phytotron were set as follows: The daylight period was
156 set to 16 hours and the environmental parameters were controlled as follows (day/night):
157 temperature (22/16°C), photosynthetically active radiation (400/0 μmol m⁻²s⁻¹) and relative air
158 humidity (55/70%). All the pots were watered from the top to 80% of the WHC of the control
159 treatments during the first week of the experiment to avoid dry soil at the bottom of the pots. All pots
160 received 100 mg N kg⁻¹ soil in a liquid solution after irrigation before sowing and the same amount 21
161 days after sowing. After one week, five spring barley (*Hordeum vulgare* L., cv. Quench) seeds were
162 sown at approximately 1 cm depth and two water regimes were established by watering the pots to
163 30% and 70% of control treatment WHC, respectively. However, treatments under the 30% water
164 regime were watered to reach 50% WHC of the control up to 10 days after sowing to secure

165 germination, whereupon 30% WHC was maintained for the rest of the experiment. Plants were
166 thinned to three plants per pot and supported with wooden plant sticks to avoid lodging. Each pot
167 received 50 g plastic beads on the top of the soil to minimize soil water evaporation. The pots were
168 watered to weight from above every second or third day during the first weeks and daily during the
169 final week of the experiment. No drainage from the pots was observed during the experiment.
170 Cumulative water consumption was calculated from the day on which all the plants had been
171 germinated until the day of harvest as the sum of water loss from each treatment recorded at each
172 watering time

173 Fig. 1 here

174 *2.4. Plant ecophysiological measurements and yield*

175 Stomatal conductance was used as an indicator of plant drought stress, as plants close stomata to
176 reduce water loss and consequently stomatal conductance decreases. Stomatal conductance
177 measurements using a leaf porometer SC-1 model (Decagon Devices) was initiated 25 days after
178 sowing and was conducted two hours after the light had been switched on. Measurements were
179 performed on the upper surface of the youngest fully emerged leaf, approximately 5 cm from the
180 stem. Three measurements per pot were taken.

181 Leaf water potential was used as an indicator of soil water availability. The leaf water potential was
182 measured 37 days after sowing in a pressure chamber using the digital plant moisture system Skye
183 SKPM 1400 connected to pressurized air (Skye Instruments Ltd., United Kingdom) on the first two fully
184 expanded leaves per pot. The measurements were performed as “pre-dawn measurements” during

185 the night, three hours after nightfall, which was approximately 20 hours after the last watering, and
186 then continued for four hours.

187 The plants were harvested six weeks after sowing by cutting the aboveground plants by hand just
188 above the soil surface. The roots were isolated by gently pressing the soil out of the pot, followed by
189 carefully rinsing the roots with water. Both shoots and roots were dried in an oven for 48 hours at
190 70°C and their dry weight determined.

191 Carbon isotope discrimination was used as an indicator of water use efficiency. Carbon isotope
192 discrimination was analyzed on the harvested aboveground dried plants. Plant samples were first
193 coarsely ground in a plant mill to pass a 4 mm sieve and secondly finely ground in a ball mill and
194 weighed into tin capsules. The carbon isotope composition was determined on an elemental analyzer
195 (FLASH 2000 Organic Elemental Analyzer, Thermo Scientific, Cambridge, UK) coupled to an isotope
196 ratio mass spectrometer using the Vienna PeeDeeBelemnite as a standard. The carbon isotope
197 discrimination (Δ) was calculated as:

198
$$\Delta (\text{‰}) = \left[\frac{(\delta_{air} - \delta_{plant})}{(1 + \delta_{plant})} \right] * 1000 \text{ (Equation 1)}$$

199 where δ_{air} was assumed to be -0.008 (Farquhar et al., 1989).

200

201 *2.5. Soil measurements*

202 Soil pH was only measured on soil samples from the 70% WHC treatments, using a soil-water
203 suspension of 5 g soil and 25 ml of Milli-Q water (pH meter Mettler-Toledo AG, Switzerland),
204 assuming no pH effects of the water regimes.

205 Pots under the 30% WHC water regime were used to determine water retention, as the root growth
206 in those pots was lower compared to the pots under 70% WHC. This made it possible to take soil
207 samples from the bottom of the pots with less root content. Undisturbed soil samples were taken
208 after harvest in a metal ring of 100 cm³. The ring was pressed into the soil from the bottom end of the
209 pot. The soil content of the pot was carefully pushed out of the pot in order to minimize disturbance
210 when cutting the intact ring with soil. The samples were saturated by adding de-aired water from the
211 bottom end and leaving the samples at zero tension for 24 hours. Moisture retention was determined
212 at suctions of 50 cm (for coarse sand) or 100 cm (for sandy loam) using a tension table with a hanging
213 water column, and at 15.5 bars suction (both soil types) using a suitable pressure plate extractor and
214 pressure chamber (Dane and Hopmans, 2002). These suction levels were chosen to represent field
215 capacity (pF 1.7 in coarse sand and 2.0 in sandy loam) and permanent wilting point (permanent
216 wilting point at pF 4.2). The samples were left for 72 hours at 50 and 100 cm tension, and for 21 days
217 at pF 4.2 to reach equilibrium. The measurements were performed in quadruplicate per treatment,
218 *i.e.* per combination of soil type and GB level.

219 Moisture content at equilibrium (m_w , g) was obtained as the difference between the masses of moist
220 and oven-dried soil (105°C). The volumetric moisture content (θ , cm³ cm⁻³) of the ring samples (*i.e.* at
221 field capacity) was calculated as water volume divided by sample volume (100 cm³) using a water
222 density of $\rho_w=1.00$ g cm⁻³. Dry bulk density was calculated from ring samples as the ratio of oven dry

223 mass (m_{sd} , g) to sample size (100 cm^3). The volumetric water content at $pF=4.2$ ($\theta_{4.2}$, $\text{cm}^3 \text{ cm}^{-3}$) was
224 calculated as:

$$\theta_{4.2} = w \frac{\rho_b}{\rho_w} \text{ (Equation 2)}$$

226 where w is the gravimetric moisture content ($w=m_w/m_{sd}$) and ρ_b is the average dry bulk density
227 measured on ring samples for the same treatment.

228 The plant AWC was calculated as the difference between volumetric water content at field capacity
229 and permanent wilting point.

230

231 *2.6. Statistical analysis*

232 Statistical analysis of the data was performed in R, version 0.98.1103. The significant interaction effect
233 of the soil type, water regime and GB addition was assessed using a three-way analysis of variance
234 (ANOVA). The effect of the water regime within each soil type was analyzed by two-way ANOVA. The
235 differences between treatments within each soil type and water regime were analyzed using least-
236 square means from the R-package lsmeans (Lenth and Herv, 2015). P values were adjusted using the
237 Tukey method. All differences at $P < 0.05$ were reported as significant. Prior to analysis, data were
238 tested for homogeneity of variance and normality of residuals using the Wally plot (R MESS package)
239 and log or square root transformed if necessary.

240 **3. Results**

241 *3.1. Shoot and root growth*

242 Shoot and root growth was affected by soil type, water regime and GB addition and type (Fig. 2). The
243 results from ANOVA analysis of single and interaction effects are shown in Table 4. Shoot and root
244 growth was lower when barley was grown in coarse sandy soil compared to the sandy loam ($p =$
245 0.0001). In the sandy loam, the 30% WHC regime had a significantly negative impact on both shoot
246 and root growth ($p < 0.0001$). Neither SGB nor WGB addition had any effect on root growth under
247 either water regime, while shoot growth decreased by the WGB addition under the 70% WHC regime.
248 In the coarse sandy soil, the 30% WHC regime had no effect on shoot or root growth in the control
249 treatments compared to the 70% WHC regime. The addition of SGB to the coarse sandy soil increased
250 shoot growth by 165% and root growth by 50% under the 70% WHC regime; however the shoot
251 biomass was still only half of the biomass obtained in the sandy loam soil. Under the 30% WHC
252 regime, the addition of SGB increased shoot growth by 40% and root growth by 57%. In contrast, the
253 addition of WGB to coarse sandy soil had no effect on shoot growth under 70% WHC, a negative
254 effect on shoot growth under 30% WHC, and no effect on root growth under either water regime.

255 Fig. 2 here

256 Table 4 here

257 *3.2. Plant ecophysiological responses*

258 Generally the water regime had an effect on the plant ecophysiological responses, while the addition
259 of GB had variable effects (Table 4). The stomatal conductance of barley leaves decreased significantly

260 under the 30% WHC regime compared to the 70% WHC regime in both soil types ($p < 0.001$, Table 4).
261 In the sandy loam soil, stomatal conductance decreased when amended with WGB under the 70%
262 WHC regime compared to the control, while there was no effect of GB addition under the 30% WHC
263 regime. In the coarse sandy soil, the application of WGB significantly decreased stomatal conductance
264 under 30% WHC, whereas there was no effect of GB under the 70% WHC. The leaf water potential of
265 barley leaves varied and was not significantly affected either by the water regimes or by GB addition
266 (data not shown).

267 The carbon isotope discrimination was highest under the 70% WHC regime and decreased
268 significantly under the 30% WHC regime in both soil types ($p < 0.0001$) (Fig. 3 c,d), confirming the
269 stomatal conductance measurements. GB amendments had no effect on carbon isotope
270 discrimination (Table 4).

271 The cumulative water consumption of barley plants overall corresponded to plant growth (Fig. 2, 4).
272 In the sandy loam soil, cumulative water consumption was affected by the water regime but not by
273 GB addition, being highest under the 70% WHC regime (Fig. 4). In contrast, in the coarse sandy soil it
274 was affected by both water regime and GB addition. SGB addition increased cumulative water
275 consumption in the 70% WHC regime, while the addition of WGB decreased it under both water
276 regimes.

277 Fig. 3 and 4 here.

278

279 *3.3. Soil measurements*

280 The application of GB did not have any effect on bulk density in either of soil types (data not shown).
281 Both soil type and GB addition affected field capacity, permanent wilting point and AWC (Fig. 5), that
282 were generally higher in the sandy loam soil compared to the coarse sand. The addition of WGB
283 increased the permanent wilting point by 9% in sandy loam and 43% in coarse sand, while the SGB
284 addition had no effect. The field capacity and AWC were increased by both GB types in both soil
285 types, although the effect was highest in the coarse sandy soil treatments. The AWC was increased by
286 18% in SGB and 17% in WGB treatment in sandy loam, while it was increased by 42% in SGB and 31%
287 in WGB treatment in coarse sand. The addition of both GBs increased the pH of the coarse sandy soil
288 (Fig. 6). The application of WGB had the highest impact and increased the pH from 6.2 to 8.3. In the
289 sandy loam soil, pH was only increased by WGB application.

290 Fig 5 and 6 here

291 **4. Discussion**

292 *4.1. Effect of reduced water supply on plants*

293 The reduced water supply affected root and shoot growth and plant water consumption in the sandy
294 loam soil considerably, while in the coarse sandy soil the differences between the two water regimes
295 were generally less pronounced. Plant growth in the control treatments in coarse sand was
296 approximately the same under both water regimes. This may be due to the fact that coarse sandy soil
297 under 30% WHC is not as close to the wilting point as sandy loam. However, the main reason is most
298 likely the limited root growth caused by mechanical resistance, which often occurs even under
299 moderately wet conditions (Whalley et al., 2006; Bengough et al., 2011). The reason for this is the
300 high soil strength of sandy particles, as greater pressure is required to push the particles aside so that
301 the root can penetrate (Barber, 1995). The applied additional water may have accumulated in the
302 bottom of the pot with fewer roots and was therefore not fully available for root uptake. Accordingly,
303 the negative effects of the reduced water regime on stomatal conductance and carbon isotope
304 discrimination in coarse sand were limited and not significantly different from the 70% WHC
305 treatment. In contrast, in the sandy loam stomatal conductance and carbon isotope discrimination
306 decreased significantly under the 30% WHC treatments as a consequence of plant water stress, which
307 is in accordance with other studies (Kammann et al., 2011; Kottmann et al., 2014). The exposure of
308 plants to drought stress typically also decreases leaf water potential (Farooq et al., 2009). However,
309 this was not observed in the current study, probably because the leaf water potential was sampled
310 pre-dawn and therefore the plants can compensate with a continuous water uptake during nighttime
311 in contrast to stomatal conductance that was measured during daytime (Schulze et al., 1985).

312

313 *4.2. The effect of SGB in sandy loam soil*

314 In the sandy loam soil, the addition of SGB increased water content at field capacity and AWC. In
315 other investigations, the effects of biochar on the hydraulic properties of loamy soils are reported to
316 vary. Several studies showed positive effects of biochar amendment to loamy sand and sandy loam
317 soils on field capacity and AWC (Abel et al., 2013; Peake et al., 2014), while no effects of biochar
318 amendment on field capacity and permanent wilting point were observed in a study by Hardie et al.
319 (2013). The varying effects are caused by the interaction of many factors such as soil texture, soil
320 organic matter content, physicochemical biochar characteristics and biochar application rate. For
321 instance, Abel et al. (2013) observed the greatest increase in AWC by biochar application in sandy
322 soils and no effect on soils with high organic matter content. In this study, the GB-induced increase in
323 field capacity and AWC was not expected to lead to an increase in shoot and root growth, as all
324 treatments were kept at either 30% or 70% WHC of the control soil. Hence, the GB-amended soils did
325 not receive higher amounts of irrigation water compared to the control soils. However, a beneficial
326 effect of increased AWC by GB on plant growth can be expected under field conditions, *e.g.* in the
327 case of thorough wetting followed by subsequent drought. The addition of SGB did not have any
328 other positive effects on shoot or root growth in the sandy loam soil under 70% WHC, which is
329 probably due to the soil's moderate clay and SOM content and a soil texture that enables root
330 development for sufficient water uptake to support plant growth. However, no positive effects of SGB
331 on plant growth under drought stress were observed either.

332

333 *4.3. The effect of SGB in coarse sandy soil*

334 In the coarse sandy soil, SGB increased water content at field capacity and AWC as well, which has
335 also been documented in other studies on coarse sandy soils (Uzoma et al., 2011; Abel et al., 2013;
336 Barnes et al., 2014). The addition of SGB resulted in considerably increased root and shoot growth
337 under both water regimes. Similar results were obtained by Kammann et al. (2011), where biochar
338 application to poor sandy soil increased the shoot and root growth of quinoa. In addition, the authors
339 reported an improvement in plant water status after the application of biochar when the same
340 limited amount of water was applied to all treatments. This contrasts with the present study where
341 plant physiological responses did not differ from the control treatments, even when biomass
342 production was significantly increased. We cannot completely exclude that the positive impact on
343 plant growth was caused by the addition of plant nutrients - such as K - to the nutrient-poor sandy
344 soil, although it was intended to avoid fertilizer effects by adding sufficient nutrients to all treatments.
345 However, the addition of mineral nutrients in WGB did not show any benefits, therefore we assume
346 that the great positive effect of SGB on plant biomass in coarse sand was most likely due to reduced
347 mechanical impedance to root growth. The importance of the soil structure can be corroborated by
348 the fact that in contrast to the sandy loam, the 70% water regime did not have a positive effect on the
349 plants in the coarse sandy soil in the non-amended control treatments, as discussed in section 4.1. We
350 hypothesize that when adding SGB to sandy soil, some of its small particles may settle between the
351 coarse sand particles, thereby reducing friction, whereas others may transform large drainable pores
352 into smaller pores. Smaller pores can improve the water supply by increasing the AWC and contact
353 between the roots and the water. This is consistent with the findings of Bruun et al. (2014), who

354 reported that SGB increased water retention in coarse sandy soil and improved root growth of barley,
355 increasing the grain yield by 22%.

356 Under field conditions, the increased AWC and improved root growth may lead to improvements in
357 both water and nutrient retention and hence decrease the leaching of mobile nutrients, such as
358 nitrate (Sika and Hardie, 2014). Improving the quality of coarse sandy soils has global potential, since
359 the lack of yield potential utilization caused by limited AWC and poor root development affects
360 agricultural production in many regions of the world, for example in parts of Africa dominated by poor
361 sandy soils (Sika and Hardie, 2014) or areas in Denmark dominated by coarse sandy subsoils (Bruun et
362 al., 2014). However, the underlying mechanisms for improving the soil structure of coarse sandy soil
363 by SGB need further investigation.

364

365 *4.4. The effect of WGB*

366 WGB increased water content at field capacity and AWC to the same extent as SGB, but no positive
367 effect on plant growth could be observed after the application of WGB in any of the soils or
368 treatments. Quite the opposite, in fact, since WGB even decreased shoot growth under the 30% WHC
369 water regime compared to the control in the coarse sandy soil. The lack of a positive effect of WGB in
370 this soil might be due to its higher proportion of larger particles (53% larger than 0.125 mm)
371 compared to SGB. Due to fewer but larger particles heterogeneously distributed in the soil, WGB may
372 not be able to change the skeleton of the soil matrix and increase the water retaining pore space
373 volume to the same degree as SGB. It may also be difficult for the roots to utilize water retained by
374 large particles of WGB. In fact, WGB addition increased the water retention at permanent wilting

375 point, indicating that WGB binds more water that is then non-available to plants. This is most likely
376 due to the high SSA and thus increased microporosity of WGB (Abel et al., 2013) and may be a reason
377 for the reduced shoot and root growth and stomatal conductance under the 30% WHC water regime
378 in coarse sandy soil. However, as the WGB addition also resulted in decreased stomatal conductance
379 and a reduction in plant biomass under the 70% WHC treatment in the sandy loam soil without a
380 decrease in water consumption, we cannot exclude other detrimental effects of this material on plant
381 growth. The WGB was most efficient at increasing soil pH. Although potentially beneficial for soil
382 fertility and crop production in acidic soils (Deal et al., 2012), this may reduce the availability of
383 certain nutrients in already alkaline soils. However, since pH was not significantly different in either
384 GB-amended treatment in the sandy loam, it seems unlikely that increased soil pH was the only
385 reason for reduced plant growth in the WGB treatment.

386

387 **5. Conclusions**

388 The reduced water regime significantly affected plant ecophysiological responses, plant growth and
389 water consumption in the sandy loam soil, whereas it only had a small or no effect in the coarse sandy
390 soil. Both gasification biochars increased the plant-available water content in both the sandy loam
391 and the coarse sandy soil. However, the two contrasting GB materials had different effects on plant
392 growth in the two soil types tested, suggesting that the mitigation of specific soil restraints needs
393 specifically adapted GB materials. The application of WGB had either no effect or slightly negative
394 effects on plant ecophysiological responses and growth. Under which conditions WGB with its
395 interesting properties such as high SSA, pH and porosity can positively affect plant growth has to be
396 the subject of future research. The greatest benefits were observed on coarse sandy soil where SGB
397 markedly increased root and shoot growth under both water regimes. These results suggest that
398 there is great potential in the ability of SGB to increase soil pH, water retention and root development
399 in order to improve crop productivity on the often poor coarse sandy soils in many parts of the world.
400 However, the results of this study are based on a pot experiment with disturbed soil and need to be
401 verified in field experiments.

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494

495

496 **Table 1** Chemical characterization and particle size distribution of the SGB (straw gasification biochar)
 497 and WGB (wood gasification biochar) materials (modified from Hansen et al. 2015)

Parameter	Unit	SGB	WGB
C	g kg ⁻¹	468	653
P	g kg ⁻¹	4	3.4
K	g kg ⁻¹	72	25
S	g kg ⁻¹	1.2	0.17
Mg	g kg ⁻¹	4.6	5.9
Ca	g kg ⁻¹	18	52
Fe	g kg ⁻¹	1.7	16
Zn	mg kg ⁻¹	64	160
Cu	mg kg ⁻¹	13	55
pH (water)		11.6	11.1
Particle size distribution	% of dry mass		
< 0.045	mm	89.3	33
0.045-0.125	mm	10.3	13.7
>0.125	mm	0.3	53.3

498

499 **Table 2** Brunauer–Emmett–Teller (BET) specific surface area (SSA) and pore volume of straw
500 gasification biochar (SGB) and wood gasification biochar (WGB). WGB was divided into two size
501 fractions (modified from Hansen et al. 2015)

Biochar	Particle size (mm)	SSA (m ² g ⁻¹)	Pore volume (cm ³ g ⁻¹)
SGB	0-1	75	0.04
WGB	0-0.5	426	0.52
WGB	0.5-1	1027	0.58

502

503

504 **Table 3** Soil texture, pH, soil organic matter (SOM) and soil water-holding capacity (WHC)

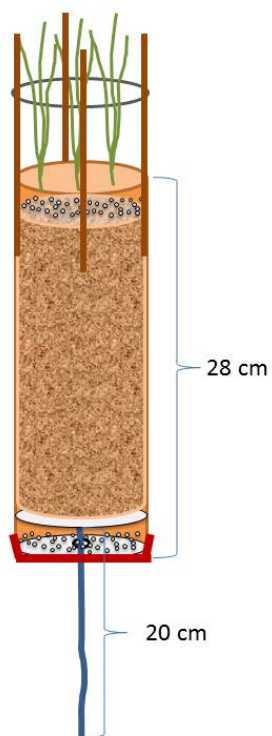
	Clay %	Silt %	Fine sand %	Coarse sand %	pH (water)	SOM %	WHC %
Sandy loam	14	14	47	24	7.9	3.4	29
Coarse sand	2.3	0.9	18.9	77.9	6.8	0.3	19

505

506 **Table 4** Results from three-way anova of single and interactions effects of soil type (Soil), gasification
 507 biochar (GB), water regime (WR) on shoot and root growth of spring barley, stomatal conductance
 508 (SC) and carbon isotope discrimination (CID)

Factors	Shoots		Roots		SC		CID	
	F-value	p-value	F-value	p-value	F-value	p-value	F-value	p-value
Soil	676.9	<0.001	44.5	<0.001	1.1	N.S.	0.2	N.S.
GB	52.4	<0.001	3.2	0.05	4.9	0.01	1.1	N.S.
WR	503.8	<0.001	33.1	<0.001	101.8	<0.001	148.5	<0.001
Soil x GB	14.9	<0.001	1.9	N.S.	1.7	N.S.	0.5	N.S.
Soil x WR	274.5	<0.001	25.7	<0.001	4.4	0.04	32.1	<0.001
GB x WR	11.2	<0.001	1.7	N.S.	2.8	N.S.	0.6	N.S.
Soil x GB x WR	3.2	0.05	1.5	N.S.	8.1	0.001	0.7	N.S.

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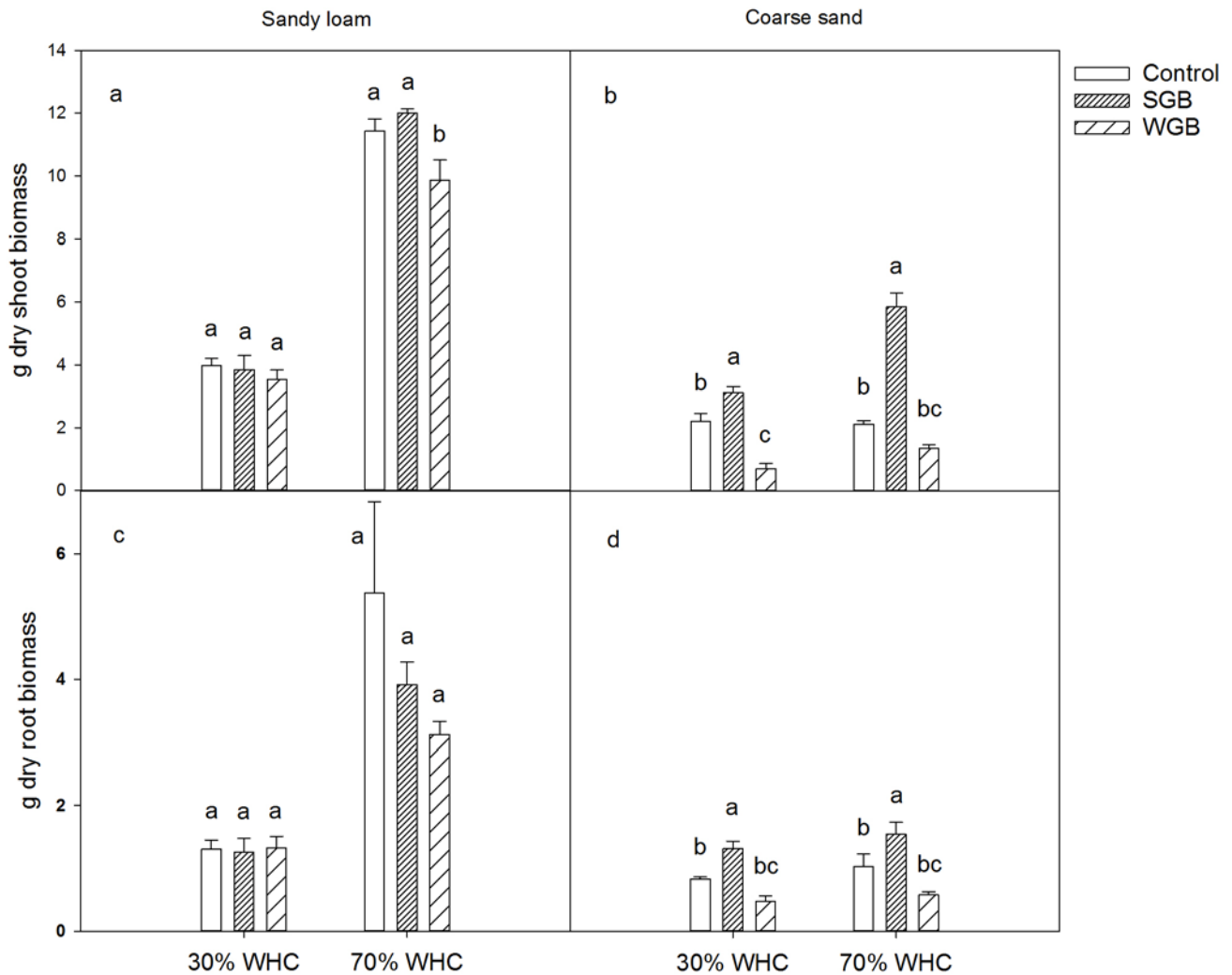
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511 **Fig. 1** The experimental setup of pots with a drainage system consisting of two layers of felted fabric
512 in the bottom with a 1 cm-thick layer of 5 mm plastic beads in between, and a 20 cm-long cotton
513 wick, attached to the inner felted fabric, passing through those layers

514

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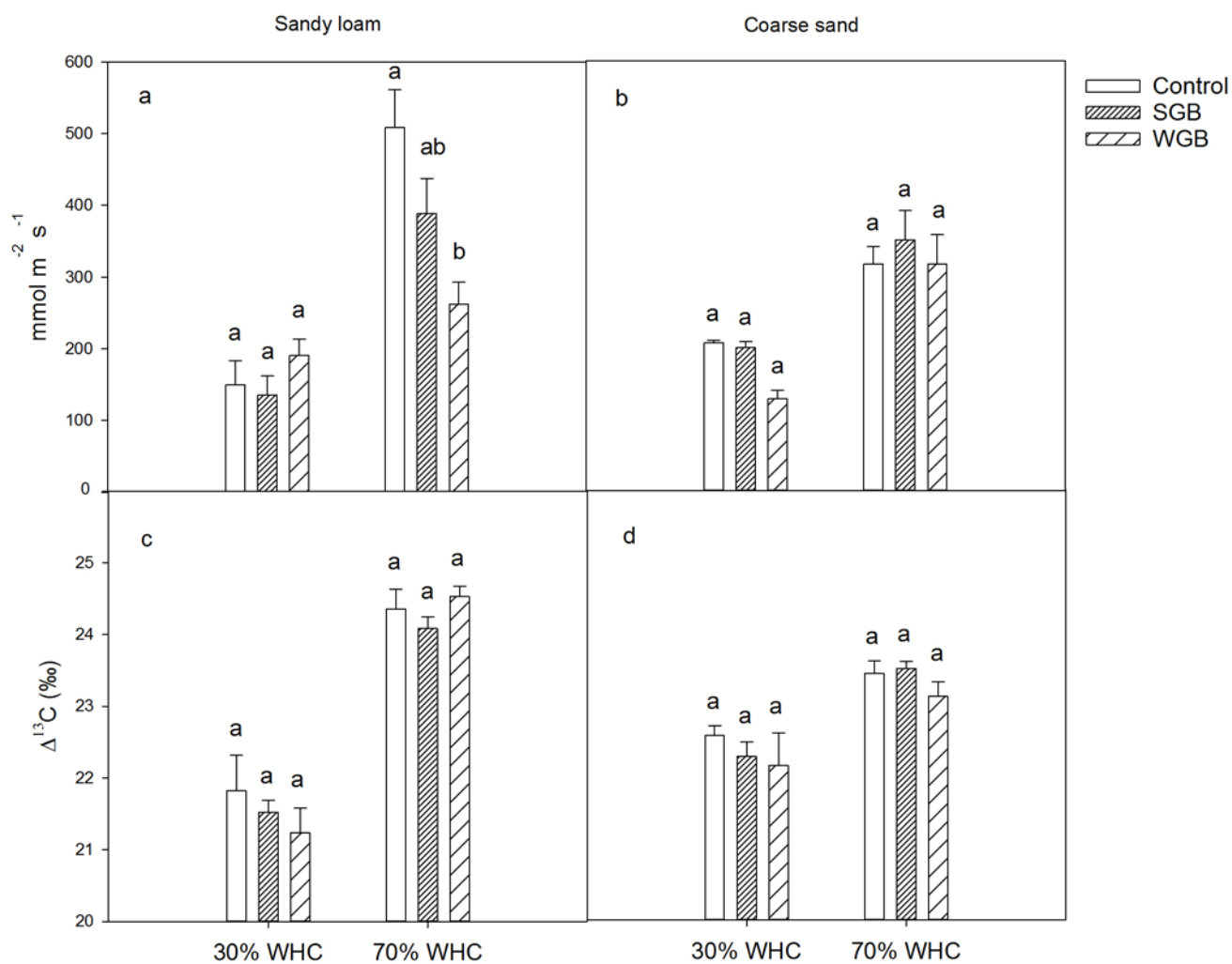
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518 **Fig. 2** Dry shoot biomass (g) of spring barley per pot after 6 weeks of the experimental period (a,b)
 519 and dry root biomass (c,d) on sandy loam soil (a,c) and coarse sandy soil (b,d) grown under two water
 520 regimes: 30% and 70% of the water-holding capacity (WHC) of the control treatment respectively.
 521 Control = non-amended soil, SGB = soil with 1% straw gasification biochar and WGB = soil with 1%
 522 wood gasification biochar. Values presented are means with standard error bars (n=4). Different
 523 letters indicate significant differences between treatments within each water regime (P < 0.05)

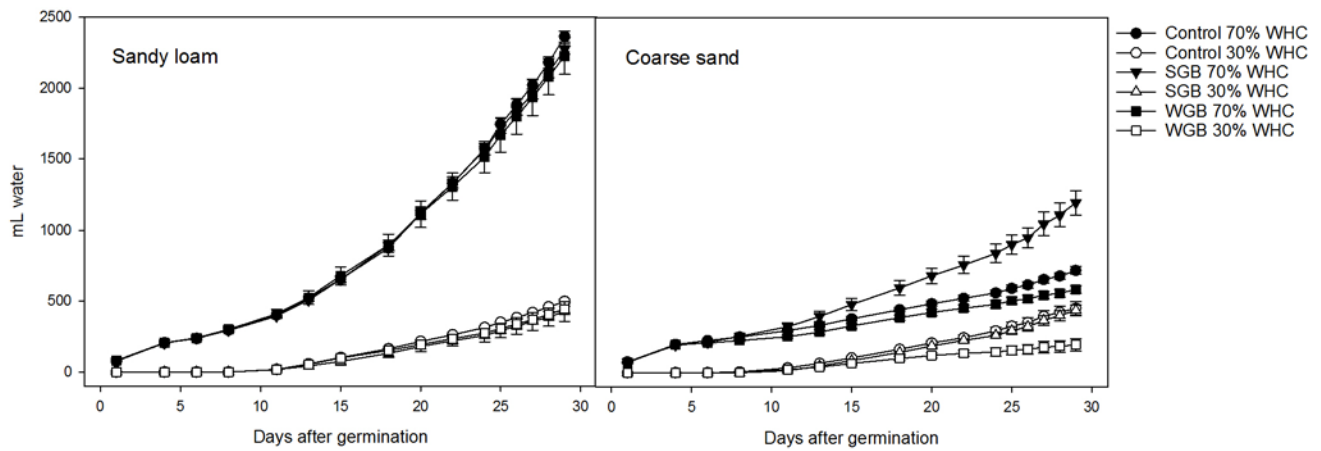
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525

526 **Fig. 3** Stomatal conductance of barley leaves (a,b) and carbon isotope discrimination in plant tissue
 527 (c,d) on sandy loam soil (a,c) and coarse sandy soil (b,d) measured under two water regimes. For
 528 treatment abbreviations, see Fig. 2. Values presented are means with standard error bars (n=4 for
 529 stomatal conductance and n=3 for carbon isotope discrimination). Different letters indicate significant
 530 differences between treatments within each water regime (P < 0.05)

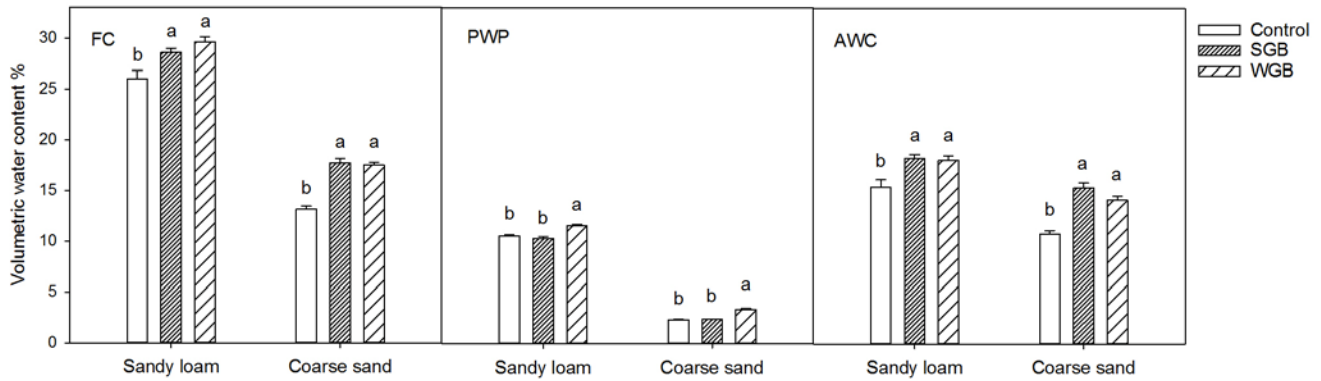
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532

533 **Fig. 4** Cumulative plant water consumption (mL water pot⁻¹) from germination until harvest in all
 534 treatments in sandy loam and coarse sandy soil respectively. For treatment abbreviations, see Fig. 2.
 535 Values presented are means with standard error bars (n=4)

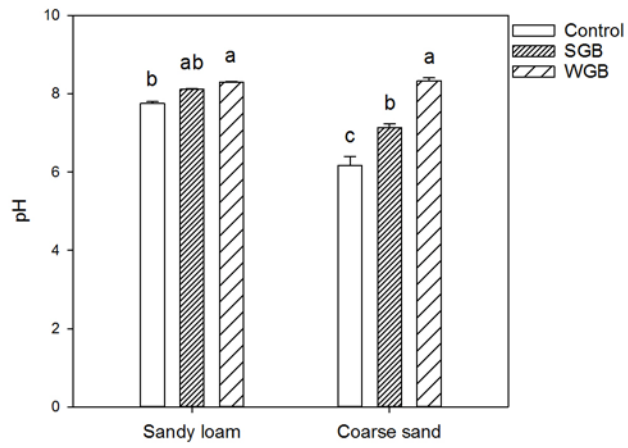
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538 **Fig. 5** Field capacity (FC), permanent wilting point (PWP) and available water content (AWC) measured
 539 at the end of the experimental period. For treatment abbreviations, see Fig. 2. Values presented are
 540 means with standard error bars (n=4). Different letters indicate significant differences between
 541 treatments within each soil type (P < 0.05)

542



543

544 **Fig. 6** Soil pH measured at the end of the experimental period. For treatment abbreviations, see Fig. 2.
 545 Values presented are means with standard error bars (n=3). Different letters indicate significant
 546 differences between treatments within soil type (P < 0.05)

547

548