Impact of hydro-/biochars on root morphology of spring wheat

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Impact of hydro-/biochars on root morphology of spring wheat

Katharina Reibe*, Klaus-Peter Götz, Thomas F. Döring, Christina-Luise Roß, Frank Ellmer

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Abstract

Despite suggested benefits of hydrochars and biochars, little is known about their effects on root development and root-char interactions. To compare effects of two types of biochar (Pyro and Pyreg) and one hydrochar (HTC) on root growth of spring wheat, two rhizobox
experiments were set up where physical contact of roots with chars was prevented using nylon gauze. Rhizoboxes were filled with unamended soil as a control or with three different soil-char mixtures (Pyro, Pyreg and HTC). Shoots and roots were harvested before flowering and at tillering in the first and second experiment, respectively. Chemical soil properties (N, K, C, pH value) were affected differently by the different chars. Both shoot and root dry matter were influenced by chars. Pyro-char had positive effects on root dry matter in both experiments. At tillering, HTC-char affected root length, root surface and number of root tips negatively. Our findings suggest that nutrients released from chars may affect root morphology of spring wheat. The comparison of different types of chars showed the varied effects on root growth, shoot growth and soil changes depending on feedstock, production process and the varied amount of chars.

**Keywords:** biochar, rhizobox, *Triticum aestivum* L., root morphology analysis

**Introduction**

Carbon plays a key role in agriculture, not only in the context of climate change mitigation but also for improving and maintaining soil fertility. One suggested way to improve soil fertility and simultaneously sequester carbon (C) to mitigate climate change is the application of biochar to soils (Laird 2008, Lehmann 2007, Lehmann et al. 2006, Lehmann et al. 2011, Sohi et al. 2010). Biochar is the product of thermal degradation of organic materials (e.g., plant residues, organic wastes) in the absence of oxygen (pyrolysis). It is distinguished from charcoal by its use as a soil amendment (Lehmann et al. 2009). An alternative product with similar functions is hydrochar. It results from the technical process of hydrothermal carbonization (HTC), which converts plant biomass low in dry matter (DM) into a carbon-rich, lignite-like product (Libra et al. 2011). This reaction takes place in aqueous milieu at temperatures between 180 and 250°C and pressures of 1.8-2.2 MPa within 4 to 12 h (Hu et al. 2010, Libra et al. 2011, Titirici et al. 2007).
Hydrochar is thought to act as a soil conditioner due to its large pore volume, and pore structure, which can vary depending on the production process (Sevilla et al. 2009, Sevilla et al. 2011a). The surface area of chars is influenced by the production process (HTC or Pyrolysis). Sevilla et al. (2011b) have measured the Brunauer-Emmett-Teller (BET) surface area of biochar, derived from barley straw, and hydrochars, produced from eucalyptus sawdust and barley-straw. Hydrochars were found to have a poorer porosity, the BET surface area values being 4.4 and 8.3 m$^2$ g$^{-1}$ for the eucalyptus sawdust and barley-straw derived hydrochar, respectively. BET surface area of the barley-straw derived biochar (153 m$^2$ g$^{-1}$) was higher (Sevilla et al. 2011b).

Despite the suggested use of different chars (hydrochars and biochars) in agriculture, little is known about their effects on root development and root-biochar interactions, impeding efforts to optimize char application in agricultural production systems. Makoto et al. (2010) showed a significant increase in root biomass (47 %) and root tip number (64 %) of Gmelin larch (*Larix gmelinii*) within a layer of char from forest fire with larch twigs, birch twigs, and shoots of dwarf bamboo buried in a Dystric Cambisol. Also, root length of rice was shown to increase with biochar additions (Noguera et al. 2010). Root weight of *Taraxacum* plants was lower when a hydrochar from beet root chips was added in different concentrations to soil (Rillig et al. 2010). Beyond these general observations, however, it is unclear in which way roots are affected by different chars at different growth stages.

In particular, there are two distinct mechanisms by which chars may influence plant roots. First, roots may grow into char pores, and this process has been observed under natural conditions (Lehmann et al. 2003). Secondly, in addition to the direct contact between roots and chars, root growth may be influenced by nutrients released from chars or via similar processes based on char-induced changes of the soil solution. While there is currently no rigorous method available to quantify root morphology if the roots are growing into char pores, it is possible to measure effects when roots have no direct contact with chars, thereby
elucidating the second mechanism of char effects on roots. In particular, when using special rhizoboxes the roots are growing between nylon gauze and can be physically prevented from making contact with chars. Although rhizoboxes have their limitations (Neumann et al. 2009), the method constitutes an almost undisturbed system and allows non-destructive monitoring of root growth.

To our knowledge, only three rhizobox experiments to analyse root development and root architecture with biochar-amended soils have been reported so far (Brennan et al. 2014, Prendergast-Miller et al. 2011, Prendergast-Miller et al. 2014). Prendergast-Miller et al. (2011) have stated that biochar addition (0, 20 and 60 t ha\(^{-1}\)) increased wheat root length ratio while plant biomass was similar between treatments. In the second study, Prendergast-Miller et al. (2014) noted that roots were attracted towards biochar. Brennan et al. (2014) have concluded that root establishment in contaminated soils can be enhanced by biochar addition but choice of biochar is important. However, there is currently no information (i) on the comparative effects of both type of chars (pyrolysis, HTC); and (ii) on the effects of chars on root morphology when roots have no access to grow into the soil and/or into char pores.

The objective of our study was therefore to investigate the effects of two different biochars produced from wood chips and maize silage and one hydrochar, from maize silage, added to a sandy soil, on the root morphology of spring wheat in rhizobox experiments. In this case, it is not possible to separate roots from the chars without destroying the root structure. Therefore, the plants were grown between nylon gauze in the environment of the soil-char mixture, thus allowing us to conduct undisturbed measurements of root morphology. We hypothesized that, depending on the different char materials and production processes, char application affects the root development and root morphology parameters differently. Further, we tested the soil chemical properties before and after char amendment, and investigated the possibility of aqueous nutrient release from chars, in order to elucidate potential non-contact mechanisms underlying the impacts of chars on crop plants.


Material and Methods

Biochar and hydrochar properties

The two biochars were produced in different ways (Mumme et al. 2013). For the first pyrolysis char (Pyro-char) ensiled whole crop maize was used as feedstock harvested in autumn 2011. The maize silage was processed by continuous pyrolysis at 600 °C for 30 minutes. Afterwards the hot char was quenched by means of water sprinkling. For the second pyrolysis char (Pyreg-char) screenings from wood chip production were processed by continuous pyrolysis at 850 °C for 30 minutes. Afterwards the hot char was quenched with water (Mumme et al. 2013).

For the hydrochar (HTC-char) ensiled whole crop maize was used as feedstock harvested in autumn 2011. The maize silage was processed by batch-wise HTC at 210 °C and 23 bar for 8 hours. Afterwards the resulting HTC slurry was separated by means of a chamber filter press (Mumme et al. 2013).

The chemical characteristics (measured by Mumme et al. 2013) differed between the used chars, with the Pyro-char showing high dry matter content and the HTC showing low ash content and a much lower pH value than the two biochars (Table 1).

Soil characteristics

Loamy sand soil was collected twice in April 2013 (Soil 1) and October 2013 (Soil 2) from the top 10 cm of arable land near Berge, Brandenburg, Germany (52° 37’ 12″ N, 12° 47’ 42″ E). After sampling, the soils were air-dried and sieved (4 mm). Two samples of each sampling were air-dried and sieved (1 mm) for chemical analysis (Table 2). Total carbon (Ct) and total nitrogen (Nt) were determined by means of elemental analysis. The samples were measured in an elemental analyser (CNS VarioMAX, Elemental Analysis GmbH, Hanau, Germany). Total organic carbon (TOC) was analysed with the VarioMAX TIC/TOC (Elemental Analysis GmbH, Hanau, Germany). Extractable P and K were measured in a
calcium lactate extract (VDLUFA I, A 6.2.1.2, 1997). The phosphorus concentration was measured spectrophotometrically from the filtrated aliquot using continuous flow analysis (San++ CFA, Skalar Analytik GmbH, Germany) and the potassium content was measured by flame photometry with atomic absorption spectroscopy (AAS 4100, Perkin Elmer, Waltham, USA). The pH value was measured with a pH electrode.

**Rhizobox experiments**

In both experiments sieved soil (21 kg) was thoroughly mixed with lightly crushed chars (Pyro, Pyreg, HTC; particle size for all materials ≤ 3 mm) to raise the organic carbon content of the soil from 0.73 % in the first experiment and 0.45 % in the second experiment (Table 2) to 1.0 %. Therefore, 82.1 g Pyro-char, 114.0 g Pyreg-char, 137.7 g HTC-char were added to the soil in the first experiment, and 167.3 g Pyro-char, 232.2 g Pyreg-char, 280.6 g HTC-char were added in the second experiment. The control treatment (Control) received no biochar.

Rhizoboxes (height: 31 cm, width: 24 cm, length: 32 cm) were constructed from Schütt Labortechnik GmbH, Germany, as described by Golldack et al. (2004) (Figure 1).

The rooting compartment and the soil or soil-char mixture compartment were separated by two pieces of nylon gauze (1µm mesh size, Heidland GmbH & Co. KG, Germany) between two Plexiglas frames. In each rhizobox two of these Plexiglas frame-nylon gauze constructions were inserted (Figure 1) and pure soil or soil-char mixtures were filled into the rhizoboxes. Each treatment was replicated three times, resulting in 12 rhizoboxes. In each rhizobox two pre-germinated (5 days old) spring wheat (*Triticum aestivum* L., cv. Chamsin, KWS, Germany) seedlings were inserted between the nylon gauze (Figure 1). For six weeks (Exp. 1) or three weeks (Exp. 2), the rhizoboxes were placed in a greenhouse (temperature: minimum 15°C, average 18 °C, maximum 21 °C; relative humidity 50-60 %, day length 12 hours).

**Plant, root and soil sampling**
In the first rhizobox experiment, wheat shoots and roots were collected at the plant-growth stage beginning of flowering (anthesis) of the main shoot (BBCH-code: 61; Meier (1997)). At sampling, plants were separated into shoots and roots grown between the nylon gauze. Shoots were cut at the stem base and dried at 60 °C for 48 h. Roots were carefully lifted within the frames and the gauze and cautiously washed to remove bound soil and char particles. After washing, the frames and nylon gauze were removed and the washed roots were scanned at 600 dpi using a flat-bed HP Scanjet 2400 for digital analyses. Afterwards, the roots were dried at 60 °C for 48 h. Root scans were digitally analysed using WinRHIZO 2012b Software (Regent Instruments, Quebec, Canada).

The set-up of the second rhizobox experiment was similar to the first experiment, with the exception that shoots and roots were collected earlier at the plant-growth stage beginning of tillering (BBCH-code: 21-23; Meier (1997)). In addition, soil samples were taken at sampling to analyse C, N, P, K and pH value with the methods described before.

Additionally, all three chars (Pyro, Pyreg, HTC) were washed in the laboratory to determine the potential desorption of N, P, K, Mg, Fe and Ca in water in order to assess plant available nutrients released from the chars. Shaking bottles (volume 500 ml) were filled with 15 ml distilled water and 5 g (2 mm sieved) of the different chars. After allowing the bottles to stand for 22 hours, 240 ml distilled water were added to each bottle, and the bottles were placed on a shaker for one hour. After that, the liquid was allowed to stand 10 minutes before being filtrated (filter: Schleicher & Schüll, hardness grade: 597.5, diameter: 210 mm). Each filtrate was then analysed for P, K, Mg, Fe, Ca using an ICP-OES ICAP 6300 (Thermo Fisher Scientific, Waltham, USA) and for C, N using a liquiTOC (Elementar, Hanau, Germany).

**Statistical analysis**

All parameters were statistically analysed with one-way ANOVA followed by Tukey’s post hoc test (at $P \leq 0.05$) to analyse significance of differences between the treatments (SPSS
Statistics Desktop 20.0 for Windows). Data were calculated as arithmetic means ± standard deviation (SD).

**Results**

*Nutrients measured in filtrate from washed chars*

Pyro-char contained the highest Mg (0.21 g (kg DM)^{-1}), K (7.80 g (kg DM)^{-1}) and P (0.55 g (kg DM)^{-1}) content (Table 3). HTC-char had the highest Ca and the lowest K content compared to Pyro-char and Pyreg-char. The hydrochar (HTC-char) had the highest content of total nitrogen bound (TNb) and TOC compared to the biochars (Pyro, Pyreg) (Table 3).

*Effect of chars on soil properties at tillering stage*

Chars had different effects on soil properties of the second experiment (Table 4). As intended, all three chars significantly altered the C_i contents from 0.62 % DM (Control) to 1.0 %, while differences between the chars were not significant. TOC was also increased in comparison to the Control, and also there were no significant differences between the three chars. However, soil amended with HTC-char had a significantly higher N_i content (0.064 % DM) compared to the Control (0.050 % DM), whereas the N_i content of soil amended with Pyro-char and Pyreg-char was not significantly different from the Control. The chars had no significant effect on plant available P. When Pyro-char was added to the soils the plant available K content increased significantly compared to the other treatments. The pH value increased significantly when soil was amended with Pyro-char and Pyreg-char (Table 4).

*Shoot and root biomass of spring wheat*

The shoot biomass of spring wheat on the beginning of flowering showed significant differences between the treatments (Figure 2a). Pyro-char had the highest shoot dry matter (2.12±0.31 g). HTC-char had also a significantly higher shoot dry matter (1.85±0.31 g) than
Control and Pyreg-char. Compared to the untreated Control, there was no negative effect on plant dry matter of spring wheat after six weeks growing in rhizoboxes (Figure 2a).

At tillering, plants growing in rhizoboxes where Pyro-char was amended to soil had the highest shoot dry matter (0.10±0.03 g) whereas HTC-char had the lowest (0.03±0.01 g) (Figure 2c). Compared to the Control, Pyreg-char had no effect on shoot dry matter of spring wheat after three weeks growing in rhizoboxes (Figure 2c).

In both experiments, wheat plants in soil amended with Pyro-char showed the highest root dry matter. At the beginning of flowering, plants in the Pyro-char treatment had a significantly higher root dry matter (0.61±0.09 g) compared to the Control (0.43±0.08 g) and Pyreg (0.38±0.08 g) (Figure 2b). At tillering, wheat plants in the Pyro-char amended soil also had the significantly highest root dry matter (0.07±0.02 g) compared to the Control (0.03±0.02 g) and HTC (0.03±0.01 g) (Figure 2d).

While there were differences in shoot and root biomass, the shoot:root ratio showed no significant differences between the treatments in both experiments (data not shown).

**Root morphology of spring wheat**

Some root parameters of spring wheat in the first (beginning of flowering) and the second (at tillering) experiment were affected differently by the different chars (Table 5).

At the beginning of flowering, Pyro and HTC had a significantly higher root length compared to Pyreg, whereas specific root length was not affected by the amended chars. The Control and Pyreg-char showed significantly higher root weight ratio compared to HTC-char. Also the plants in the Control treatment (2.45±0.63 cm mg⁻¹) had a significantly higher root length ratio than those in the Pyro treatment. There were no significant char effects on root surface area and root tip number, but the number of root tips increased on average 3.3 times compared to tillering (Table 5).

Compared to the influences of amended chars on root traits at the beginning of flowering, the effect of amended chars on root traits of spring wheat at tillering were different (Table 5).
Pyro-char and Pyreg-char as well as the Control had a significantly higher root length compared to HTC-char. Specific root length showed significant differences between the char treatments with a difference between Pyreg-char and HTC-char. Root weight ratio was significantly influenced by HTC-char compared to the Control, but root length ratio was not affected. Pyro-char had a significantly larger root surface than HTC-char (Table 5). Also, the number of root tips in soil treated with HTC-char was significantly lower compared to soil treated with Pyreg-char.

**Discussion**

*Influence of feedstock and production process on chemical characteristics of chars*

Feedstocks and production processes differed among the chars used in our experiments. Therefore, distinct effects on shoot and root growth of spring wheat can be expected (Bargmann et al. 2014, Brennan et al. 2014, Prendergast-Miller et al. 2014). Pyro-char which was produced from the ensiled whole crop maize had positive effects on root growth in both experiments. In contrast, the hydrochar (HTC-char) produced from the same feedstock (ensiled whole crop maize) showed positive effects on shoot and root growth in the first experiment but negative effects in the second. Although both chars were produced from the same feedstock, the production processes differ. As a result of the different production processes the chars (Pyro, HTC) had distinct chemical characteristics (Table 1). With regard to pH, Pyro-char and Pyreg-char showed higher values than HTC-char (Table 1), which confirms similar results obtained by Sun et al. (2014). Pyro-char had higher contents of Ca, Fe, Mg, K, P compared to the HTC-char, which is consistent with the study reported by Sun et al. (2014).

Pyro-char and Pyreg-char were produced from different feedstocks and also differed with regard to process parameters. Screenings from wood chip productions were processed by continuous pyrolysis at 850 °C for 30 minutes for the production of Pyreg-char (Mumme et al. 2014)
In general wood biochars (here Pyreg-char) had higher total C, lower ash content and lower total N, Fe, Mg, K and P contents compared to manure-based biochars (Singh et al. 2010). The pyrolysis temperature of Pyreg-char was higher than the temperature of Pyro-char and the feedstock differed. Higher pyrolysis temperatures up to 600 °C increased the carbon content of biochars in the study of Sun et al. (2014). In comparison to Pyro-char, Pyreg-char had a higher C/N ratio and Ca content (Table 1). While procedural or chemical differences between Pyro-char and Pyreg-char did not result in significantly different effects on plants at tillering (Figure 2), plants at the beginning of flowering showed both higher below-ground and aboveground growth when soil was amended with Pyro-char than when Pyreg-char was used.

Chemical characteristics of the filtrate of chars

The chars were washed with distilled water to study whether nutrients were soluble and plant available (Table 3). In a previous study, for example, chars were treated with Milli-Q-water (Wu et al. 2011) to analyse char-bound nutrients. Here we used distilled water instead. The filtrate of Pyro-char had the highest Fe, Mg, K and P concentrations compared to Pyreg-char and HTC-char. This should be the reason for the positive effects of Pyro-char on spring wheat plants in both experiments. Prendergast-Miller et al. (2014) reported that roots are attracted towards biochars. They conclude, that plant roots respond to soil amendments because biochar can serve as a direct nutrient supply through the addition of P and N. In our observations a reason for roots attracted towards biochars could be the available nutrient content (especially K) for the roots.

Generally, however, conclusions about the chemical mechanisms by which chars may have affected the wheat plants are limited by the fact that neither micronutrients nor toxins potentially linked to pyrolysis were analyzed in this study, and not information was obtained on the recalcitrance of the chars. Further studies are therefore required to elucidate the role of these factors on plant growth when amending soil with various kinds of char.
**Biochar and hydrochar effects on soil characteristics**

HTC-char had a positive effect on the total N content (Table 4) compared to the Control. The reason is the higher N content of the hydrochar (HTC-char) (Table 1). However, biochars had no influence on total N content compared to the Control (Table 4). The total N content did not increase when greenwaste biochar was added to soil at different rates (Chan et al. 2007). In general, a nitrogen fertilization effect from the chars in our experiments is unlikely, because small amounts of N were added to soil with the chars.

Plant available P was not affected by char addition (Table 4), because chars had a low P content and therefore in the second experiment only little P was added to soil with chars. In relation to the amount of P available in the Control, only 1-4 % was added with the chars. This suggests that there was no phosphorus fertilization effect with the addition of chars to soil in the second experiment. In comparison, Kloss et al. (2014) reported that the extractable P content was significantly higher compared to the Control when biochars were added to the substrate. In contrast, Pyro-char had a positive effect on the plant available K content in the soil. Pyro-char had a higher K content (32.26 g kg\(^{-1}\)) compared to Pyreg-char and HTC-char. In relation to the unamended soil, 40 % K was added when Pyro-char was added to soil. Because K is known to have positive effects on water budget and photosynthesis (Cooper et al. 1967, Terry et al. 1973), the growth promoting effects of Pyro-char observed in both rhizobox experiments might be interpreted as a result of a K fertilization effect.

There were also significant differences in pH values (Table 4). Pyro-char and Pyreg-char showed a higher pH value compared to the Control and HTC.

**Influence of sampling date and different amounts of chars on shoot and root development**

Compared with shoot-dominated phenomena, less is known about root systems, the rhizosphere and root-shoot interactions during plant growth and development, because sample acquisition and analysis of root morphology are tedious, time-consuming, and often
inaccurate (Zoon et al. 1990). When using rhizoboxes for studying root development, the roots are growing between nylon gauze and can be physically prevented from making contact with chars and soil. The mesh size of nylon gauze of only 1 µm was used to exclude that root hairs (12 µm diameter) (Singh Gahoonia et al. 1997) have the possibility to grow through the nylon gauze. Prendergast-Miller et al. (2014) observed that direct interactions between woody biochar particles and wheat roots facilitate nutrient and water uptake. Our method is suitable to understand why the roots are attracted towards chars; in particular, because roots were affected by the chars but had no possibility to grow into char pores, char effects are most likely to have occurred through char-mediated changes in the soil solution.

In the first experiment plants were sampled at the beginning of flowering which is an important growth stage for yield development, but for our investigations the second experiment (tillering) is more relevant. It is possible that the chars may have relevant influences at the first vegetative stages and others at the beginning of flowering (generative) (Figure 2). However, it is also possible that the higher amounts of chars in the second experiment have an effect on the development of roots and plants. In both experiments, Pyro-char had positive effects on shoot and root growth (Figure 2) independently of the amounts of chars. In the first experiment 137.7 g HTC-char was added and in the second 280.6 g to soil.

At the beginning of flowering HTC-char had a significant positive effect on plant dry matter compared to the Control and Pyreg-char (Figure 2a). Compared to the growth-stage beginning of flowering, the plant dry matter was negatively influenced by the higher amount of HTC-char at tillering stage (Figure 2c). Thus, the different influences of HTC-char can be an effect of growth stage and/or the specific amounts used. Early growth reduction of sugar beet was observed when hydrochar was combined with low N fertilizer level (Gajić et al. 2012). The higher amount of HTC-char combined with the sampling at an earlier growth stage in the second experiment (tillering) could be the reason for the negative effects on shoot and root dry matter compared to Pyro-char.
**Root morphology**

HTC-char and Pyro-char had a positive effect on root length of spring wheat compared to Pyreg-char in the first experiment (beginning of flowering). Possible reasons for this include the different feedstocks of the chars, the different char process parameters or a combination of both; however, our experiment did not allow identifying which of these contributed to the observed effects. In the second experiment, HTC-char had a negative effect on root length compared to the Control, Pyreg-char and Pyro-char (Table 5) due to the higher amounts of chars. Root surface of spring wheat growing in soil amended with HTC-char was significantly lower compared to Pyro and Pyreg in the second experiment (at tillering). The specific root length (length per unit weight of root) was not affected in the first experiment, but in the second experiment HTC had significantly lower specific root length than Pyreg (Table 5). Roots with high specific root length are often found in plants grown under nutrient deficient conditions (Fitter 1985).

The influence of HTC-char on root weight ratio was also different. While at the growth-stage beginning of flowering HTC had the lowest root weight ratio compared to the Control and Pyreg, at tillering stage it had the highest compared to the Control. Different amounts of HTC-char and the low shoot dry matter (Figure 2c) are potential reasons for the different effects of HTC-char. In particular, nutrient deficiency may induce a higher root growth compared to shoot growth to compensate the lack of nutrients (Drew et al. 1973). Further studies are required to test this hypothesis and to investigate the interaction between char amendment and nutrient availability, in particular nitrogen, as this macronutrient is a key driver of plant growth.

**Conclusion**

Our study shows that rhizoboxes are suitable for studying shoot and root growth in varied growth stages and to answer the question how root morphology of spring wheat is affected by
different chars, when growing in the environment of soil amended with chars. Further, our findings show that the char nutrient content may be an important factor for the different effects on shoot growth, root growth and root morphology. By preventing roots from making contact with char-soil mixtures, we were able to show that roots were influenced by chars even when physical contact between roots and char-soil mixtures is not possible. This suggests that nutrient release from chars may directly influence crops. Hydrochar had a lower pH value and carbon content than biochar. The type of feedstock and process parameters of pyrolysis affected the chemical characteristics of chars. The nutrients of chars could be washed out and transported by the soil solution, which have an effect on shoot and root development. When soil was amended with chars the soil chemical characteristics were influenced in different ways. Further, sampling date and the amount of chars may both be important for the influences of chars on shoot dry matter, root dry matter and root parameters, our study does not allow to separate sampling date and amount of char from each other. It is possible that the influences of chars varied between the first growth stages (vegetative) and the generative growth stages. However, the comparison of different type of chars showed the varied effects on root growth, shoot growth and soil changes depending on feedstock, production process and the amount of chars. However, as the differences between chars observed in our study show, further investigations are required into the production process and the effects of different feedstocks of chars. With this information, more targeted recommendations can be given on how char application in agriculture can contribute to raising carbon content of soils sustainably and to optimizing effects on crop plants.

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References


Table 1. Chemical characteristics of the chars.

<table>
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<tr>
<th>Characteristics</th>
<th>Pyro-char</th>
<th>Pyreg-char</th>
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<tr>
<td>DM (% FM)</td>
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<td>TOC (% DM)</td>
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<td>1.29</td>
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</table>

Notes: Data were modified from Mumme et al. (2013). FM, fresh matter; DM, dry matter; TOC, total organic carbon.

Table 2. Chemical characteristics of the soils used for rhizobox experiments (n=2).

<table>
<thead>
<tr>
<th>Soil samplings</th>
<th>C_t (% DM)</th>
<th>TOC (% DM)</th>
<th>N_t (% DM)</th>
<th>P (mg kg^{-1})</th>
<th>K (mg kg^{-1})</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil 1 (April) (Experiment 1)</td>
<td>0.79</td>
<td>0.73</td>
<td>0.07</td>
<td>0.10</td>
<td>0.12</td>
<td>6.2</td>
</tr>
<tr>
<td>Soil 2 (October) (Experiment 2)</td>
<td>0.60</td>
<td>0.45</td>
<td>0.04</td>
<td>0.12</td>
<td>0.15</td>
<td>6.7</td>
</tr>
</tbody>
</table>

Notes: DM, dry matter; C_t, total carbon; N_t, total nitrogen; TOC, total organic carbon.
Table 3. Chemical characteristics of the filtrate of the chars (n=2).

<table>
<thead>
<tr>
<th>Material</th>
<th>Ca</th>
<th>Fe</th>
<th>Mg</th>
<th>K</th>
<th>P</th>
<th>TNb</th>
<th>TOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pyro-char</td>
<td>0.15</td>
<td>0.02</td>
<td>0.21</td>
<td>7.80</td>
<td>0.55</td>
<td>0.66</td>
<td>47.46</td>
</tr>
<tr>
<td>Pyreg-char</td>
<td>0.13</td>
<td>0.01</td>
<td>0.03</td>
<td>4.61</td>
<td>0.10</td>
<td>0.74</td>
<td>41.46</td>
</tr>
<tr>
<td>HTC-char</td>
<td>0.27</td>
<td>0.02</td>
<td>0.13</td>
<td>1.23</td>
<td>0.26</td>
<td>4.96</td>
<td>201.13</td>
</tr>
</tbody>
</table>

Notes: DM, dry matter; TNb, total nitrogen bound; TOC, total organic carbon

Table 4. Chemical characteristics of soil samples from the second rhizobox experiment. (Data were shown as means of three replicates ± SD).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>C$_t$</th>
<th>TOC</th>
<th>N$_t$</th>
<th>P</th>
<th>K</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(% DM)</td>
<td>(g kg$^{-1}$)</td>
<td></td>
<td>(g kg$^{-1}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>0.62 ±0.03</td>
<td>0.43 ±0.03</td>
<td>0.050 ±0.002</td>
<td>0.102 ±0.004</td>
<td>0.137 ±0.019</td>
<td>6.84 ±0.04</td>
</tr>
<tr>
<td>Pyro</td>
<td>1.00 ±0.04</td>
<td>0.82 ±0.09</td>
<td>0.060 ±0.002</td>
<td>0.120 ±0.013</td>
<td>0.182 ±0.013</td>
<td>7.00 ±0.00</td>
</tr>
<tr>
<td>Pyreg</td>
<td>1.03 ±0.10</td>
<td>0.80 ±0.15</td>
<td>0.059 ±0.002</td>
<td>0.113 ±0.009</td>
<td>0.147 ±0.005</td>
<td>7.11 ±0.03</td>
</tr>
<tr>
<td>HTC</td>
<td>0.98 ±0.04</td>
<td>0.86 ±0.064</td>
<td>0.064 ±0.007</td>
<td>0.112 ±0.012</td>
<td>0.124 ±0.010</td>
<td>6.71 ±0.03</td>
</tr>
</tbody>
</table>

Notes: Within columns, numbers followed by the same letter are not significantly different from each other (P ≤ 0.05). C$_t$, total carbon; N$_t$, total nitrogen; TOC, total organic carbon.
Table 5. Root morphology parameters of spring wheat in soil (Control) and soil amended with chars (Pyro, HTC, Pyreg). Data are means ± SD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Control</th>
<th>Pyro</th>
<th>HTC</th>
<th>Pyreg</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>First experiment (beginning of flowering)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root length</td>
<td>cm</td>
<td>2758±418</td>
<td>3063±395</td>
<td>3042±388</td>
<td>2249±228</td>
</tr>
<tr>
<td>Specific root length</td>
<td>Root length/root biomass (cm mg⁻¹)</td>
<td>7.64±2.75</td>
<td>5.08±0.29</td>
<td>7.25±1.95</td>
<td>5.65±1.16</td>
</tr>
<tr>
<td>Root weight ratio</td>
<td>Root biomass/plant biomass (mg mg⁻¹)</td>
<td>0.33±0.06</td>
<td>0.29±0.03</td>
<td>0.24±0.04</td>
<td>0.34±0.06</td>
</tr>
<tr>
<td>Root length ratio</td>
<td>Root length/plant biomass (cm mg⁻¹)</td>
<td>2.45±0.63</td>
<td>1.45±0.08</td>
<td>1.70±0.39</td>
<td>1.88±0.43</td>
</tr>
<tr>
<td>Root surface</td>
<td>cm²</td>
<td>549±118</td>
<td>720±94</td>
<td>651±94</td>
<td>569±67</td>
</tr>
<tr>
<td>Root tips</td>
<td>numbers</td>
<td>3534±1088</td>
<td>3066±304</td>
<td>2969±897</td>
<td>2296±231</td>
</tr>
<tr>
<td><strong>Second experiment (tillering)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Root length</td>
<td>cm</td>
<td>780±238</td>
<td>1126±194</td>
<td>391±58</td>
<td>1069±306</td>
</tr>
<tr>
<td>Specific root length</td>
<td>Root length/root biomass (cm mg⁻¹)</td>
<td>29.48±11.13</td>
<td>18.92±8.56</td>
<td>12.89±3.21</td>
<td>35.61±19.36</td>
</tr>
<tr>
<td>Root weight ratio</td>
<td>Root biomass/plant biomass (mg mg⁻¹)</td>
<td>0.53±0.26</td>
<td>0.73±0.26</td>
<td>1.07±0.48</td>
<td>0.58±0.21</td>
</tr>
<tr>
<td>Root length ratio</td>
<td>Root length/plant biomass (cm mg⁻¹)</td>
<td>14.07±4.66</td>
<td>13.23±5.89</td>
<td>12.73±2.51</td>
<td>17.55±3.36</td>
</tr>
<tr>
<td>Root surface</td>
<td>cm²</td>
<td>140.96±44.48</td>
<td>205.78±31.56</td>
<td>70.25±8.96</td>
<td>182.42±77.46</td>
</tr>
<tr>
<td>Root tips</td>
<td>numbers</td>
<td>860±222</td>
<td>950±163</td>
<td>722±170</td>
<td>1143±344</td>
</tr>
</tbody>
</table>

Notes: Within rows, numbers followed by the same letter are not significantly different from each other (P ≤ 0.05).
Figure 1. Schematic representation of a rhizobox used for experiments 1 and 2.
Figure 2. Spring wheat at the beginning of flowering (first experiment, six weeks) (a,b) and at tillering (second experiment, three weeks) (c,d), showing the response of above ground shoot dry matter (a, c), root dry matter (b, d). Data are means ± SD. Different letters indicate significant differences between the treatments (P ≤ 0.05).