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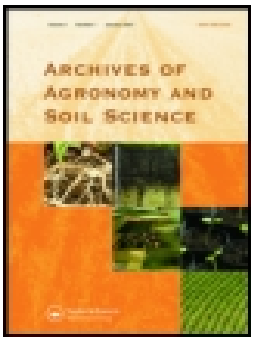
Citation for published version:
Sänger, A, Reibe, K, Mumme, J, Kaupenjohann, M, Ellmer, F, Roß, C & Meyer-aurich, A 2016, 'Biochar application to sandy soil: effects of different biochars and N fertilization on crop yields in a three-year field experiment', *Archives of Agronomy and Soil Science*. https://doi.org/10.1080/03650340.2016.1223289

Digital Object Identifier (DOI):
10.1080/03650340.2016.1223289

Link:
Link to publication record in Edinburgh Research Explorer

Document Version:
Peer reviewed version

Published In:
Archives of Agronomy and Soil Science



Archives of Agronomy and Soil Science

ISSN: 0365-0340 (Print) 1476-3567 (Online) Journal homepage: http://www.tandfonline.com/loi/gags20

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Publisher: Taylor & Francis
Journal: *Archives of Agronomy and Soil Science*
DOI: 10.1080/03650340.2016.1223289

Biochar application to sandy soil: effects of different biochars and N fertilization on crop yields in a three-year field experiment

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Abstract

During the last years, most biochar studies were carried out on tropical soils whereas perennial field experiments on temperate soils are rare. This study presents a 3-year field experiment regarding the effects of differently produced biochars (pyrolyzed wood, pyrolyzed maize silage, hydrothermal carbonized maize silage) in interaction with digestate incorporation and mineral N fertilizer application on soil C and N, crop yields of winter wheat, winter rye and maize, and the quality of winter wheat. Soil C and plant available potassium were found to be significantly positive affected by pyrolyzed wood biochar whereas the latter only in combination with N fertilization. Crop yields of winter wheat, winter rye and maize were not affected by biochar and showed no interaction effects with N fertilizer supply. Wheat grain quality and nutrition contents were significantly affected by biochar application, e.g. highest amounts of phosphorous, potassium and magnesium were determined in treatments amended with pyrolyzed maize silage biochar. Biochar induced an improved availability of plant nutrients, which apparently were not yield limiting in our case. These results limit the potentials of biochar for sustainable intensification in agriculture by increasing crop yields for the temperate zones. However, detection of other environmental benefits requires further investigations.

Keywords: Biochar; field experiment; temperate soil; crop yields; wheat grain quality

Introduction

The growing world population and increasingly scarce land and freshwater resources have induced a discussion on "sustainable intensification" in agriculture (Garnett et al. 2013, Godfray and Garnett 2014). While productivity growth in agriculture grew faster than the world population in the past 50 years, long term projections of the rate of crop yield growth for the most important agricultural crops is decreasing (Food and Agriculture Organization of the United Nations 2014a). Although land use could be expanded to meet the growing demand to some degree, this could only be realized at high environmental costs which illustrate the need to intensify the agricultural production (Garnett et al. 2013). As one potential solution the use of biochar as soil amendment was progressively investigated during the last years due to the assumed beneficial effects on soil properties, e.g. soil pH, cation exchange capacity, soil water holding capacity, long term carbon (C) sequestration, and on crop yield and the potential of greenhouse gas mitigation (Chan et al. 2007, Van Zwieten et al. 2010, Case et al. 2012, Biederman and Harpole 2013, Cayuela et al. 2014).

Biochar is a C-rich material produced by different thermochemical biomass conversion processes (e.g. by pyrolysis and hydrothermal carbonization (HTC)). Pyrolysis is a dry carbonization technique typically operated at 400-800°C, whereas HTC is a wet process with temperatures in the range of 170-280°C and pressures of 10-80 bar. HTC can therefore use wet biomass without prior drying and generally achieve a higher yield of solid C product than pyrolysis but with relatively low biological stability and porosity (Libra et al. 2011). Variation in process design and feedstock (e.g. wood, crop residues and animal manures) results in biochars with various physical and chemical properties (Brewer et al. 2011, Meyer et al. 2011) and therefore varying impacts on soil properties and crop production.

A meta-analysis of Biederman and Harpole (2013) based on 371 studies from 114 independent publications showed the variance of possible effects of biochar on plant productivity and nutrient cycling. The meta-analysis of Jeffery et al. (2011) showed an overall small (approximately 10%) positive effect of biochar amendment to soils on crop productivity. However, most of previous experiments were conducted in tropical environments with typically acidic soils, low contents of plant nutrients and soil organic matter, which can hardly be transferred to temperate zones where typical soil conditions of the tropics are not common (Tammeorg et al. 2014a). Research activities of biochar applications to temperate soils in perennial field experiments started recently (Gurwick et al. 2013, Borchard et al. 2014, Liu et al. 2014, Nelissen et al. 2015). Moreover, available research results do not provide a clear picture of crop yield response in the temperate zones, as has been stated for the whole world by the meta-analysis by Jeffery et al. (2011). For example, Kloss (2014) reported about depressed mustard (*Sinapis alba* L.) and barley (*Hordeum vulgare* L.) yields and unaffected clover (*Trifolium pretense* L.) yields within a one year greenhouse experiment after the application of three different biochars (pyrolyzed wheat straw, pyrolyzed mixed woodchips and pyrolyzed vineyard pruning). In pot and field experiments with maize (*Zea mays* L.) in Germany (pot experiment) and North America (field experiment) no yield effects were found after the application of biochar (Guerena et al. 2013, Borchard et al. 2014). Latest research has shown that yield response to biochar application interacts with fertilizer supply (Blackwell et al. 2010, Schulz and Glaser 2012, Guerena et al. 2013) as well as with an enrichment of biochar with nutrients (Gunes et al. 2014, Reverchon et al. 2014) or the concurrent application of nutrient rich organic matter (Steiner et al. 2007), which may be an explanation for the mixed results of crop yield response in studies with biochar from the temperate zones. Furthermore, fermentation of biochars with biologically active digestate may contribute to the degradation of volatile organic compounds that are potentially phytotoxic (Bargmann et al. 2013, Becker et al. 2013). However, information on the comparative effects of biochars originated from pyrolysis or HTC in combination with or without digestate and fermentation on soil properties and crop yield is still lacking.

Most biochar field studies focused on the changes of soil quality and yield effects (Lehmann et al. 2003, Chan et al. 2007, Steiner et al. 2007, Asai et al. 2009, Van Zwieten et al. 2010, Vaccari et al. 2011, Jones et al. 2012). To our knowledge, only few studies included crop growth and development, yield components, nutrient contents and quality of crop products (Chan et al. 2007, Tagoe et al. 2008, Uzoma et al. 2011, Jones et al. 2012, Schmidt et al. 2014, Tammeorg et al. 2014a). For example, Tammeorg et al. (2014a) reported that the seed number per plant of faba bean (*Vicia faba* L.) and turnip rape (*Brassica rapa* L.) was significantly higher when grown with biochar. Moreover, phosphorus (P) uptake and nitrogen (N) use efficiency by plants were increased after biochar addition to soil (Reddy et al. 2013).

This paper aims to contribute to the question of the effects of differently treated biochars on crop yields of winter wheat (*Triticum aestivum* L.), winter rye (*Secale cereale* L.) and maize (*Zea mays* L.), the yield components and grain quality of winter wheat as well as on the C content in the soil. Therefore, we have set up a three-year field experiment focusing on two research objectives, which were evaluated separately. We investigated (I) the impact of biochars originated from wood or maize silage, carbonized by pyrolysis or HTC and treated with or without digestate and (II) the interaction of biochar from pyrolyzed wood and mineral N fertilization on crop yields and soil C content.

Materials and Methods

Preparation and post-treatment of the biochars

Three different biochars were used for the investigations. One biochar (W(py)) was produced by Pyreg (Dörth, Germany) from a mixture of deciduous and coniferous wood chips by means of a screw pyrolyzer. The inlet gas temperature of the reactor's heating jacket was 850 °C (± 20 °C) and the temperature of the material increased to up to 900 °C. The hot char was quenched with water to about 40% dry matter (DM). The second biochar (M(py)) was obtained from Regenerative Energie Wirtschaftssysteme GmbH (Quakenbrück, Germany) produced from ensilaged whole crop maize using a continuous pyrolyzer with a nominal throughput of 150 kg h^{-1}. The pyrolyzer (Regenis MAX) is a staged system with consecutive steps for drying, degassing, and pyrolysis along the horizontal material flow. The biochar used in this study was produced at a pyrolysis temperature of 600 °C (30 min), a throughput of 100 kg h^{-1}, and slight negative pressure of 5 mbar. Afterwards the hot char was quenched by means of water sprinkling. The third biochar was obtained by batch-wise HTC of ensilaged whole crop maize at 210°C and 23 bar for 8 h (M(htc)). After the carbonization process the resulting HTC slurry was separated into a solid and a liquid phase by means of a chamber filter press.

Digestate was obtained from biogas production using ensilaged whole crop maize. The maize silage was digested by a batch-wise solid-state process at mesophilic temperatures (approx. 35°C). For biochars M(py) and M(htc) digestate was added for subsequent fermentation resulting in biochars named M(py)+D and M(htc)+D. In order to obtain suitable conditions for methanogenic fermentation the biochars were mixed with digestate and water. For fermentation, a C based digestate to substrate ratio of 1:2 was aspired. By means of water addition, each mixture was intended to show a DM content of 25-30%. Approximately 460 kg of M(py) and 1170 kg of M(htc) was mixed with 1850 kg of digestate, respectively, as well as 860 kg (for M(py)) and 400 kg (for M(htc)) of water. The mixtures were filled in flexible intermediate bulk container (FIBCs). In order to establish anaerobic conditions the FIBCs were wrapped in silage plastic. Mesophilic temperatures were maintained by placing the FIBCs on a water-heated concrete plate and covered with an additional plastic sheet. After 29 days the fermentation was stopped and the FIBCs were removed from the heated concrete plate. As expected, the incorporation of digestate to biochar and subsequent fermentation decreased the C content and increased the content of ash, when compared to the raw biochars (Table 1). All major nutrients were enriched, except for the potassium (K) content of M(py)+D, which decreased slightly. Further, M(htc) received a strong increase in pH (5.25 to 7.03) and electrical conductivity (EC) (0.30 to 1.24 S m^{-1}), whereas the pH and EC of M(py) were slightly lower after fermentation (Table 1). Digestate addition to W(py) was made by mixing biochar and biochar directly before field application.

[Table 1 near hear]

Field experiment

The field experiment was carried out in Berge near Potsdam (State of Brandenburg, Germany; N52° 37' 11.91" E12° 46' 0.268"), an agricultural experimental station of the Institute of Agricultural and Urban Ecological Projects. The site is located 45 m above sea level; mean annual temperature at this site is 8.7°C and the mean annual precipitation 503 mm. According to the classification of the Food and Agriculture Organization of the United Nations (2014b) the soil at the location of the field experiment can be classified as Cambisol, with a sandy loam texture (71% sand, 22% silt, and 7% clay), an initial total C (C_t) and N (N_t) content of 7.3 and 0.7 g kg^{-1} in the upper 20 cm of the soil, respectively, a moderate fertility (soil fertility index 35), a pH value of 6.0 and double lactate soluble P (P_{dl}) and K (K_{dl}) contents of 0.05 and 0.11 g kg^{-1} dry soil, respectively. The field has been planted with cereals and maize in rotation in the past. The previous crop before the beginning of the field trial was oat (*Avena sativa* L.); the last application of organic fertilizer (solid digestate) was in 2010.

The field experiment was set up in September 2012 with a three-factorial randomized complete block design. Four blocks were aligned parallel to a hedge at one side of the field which could have an impact on the experiment (Figure 1 a)). Each plot has a size of 4.5 x 10 m, containing an investigation area (1.5 x 9 m) and a harvest area (1.5 x 8 m) (Figure 1 b)). Investigation area provided opportunities to take soil samples, whereas the harvest area remained undisturbed for yield investigations.

[Figure 1 near hear]

The experimental factors were biochars (BC), digestate incorporation (D), and levels of mineral N fertilizer applications (fN). In total 14 treatment combinations, varying in origin of input material for biochar production, biochar production methods, type of digestate incorporation and fertilization intensity, were randomized in each block. Not all combinations of treatments were realized; therefore, two specific orthogonal groups (OG's) (Table 2) were selected to evaluate the research questions with the present design. Treatments of OG1 were used to analyze the impact of biochars originated from wood or maize silage, carbonized by pyrolysis or HTC and treated with or without digestate. The OG2 evaluated the interaction of biochar from pyrolyzed wood and different mineral N fertilization rates.

In September 2012 the biochars W(py), M(py), M(htc), M(py)+D and M(htc)+D were applied at a rate of 7.7 t ha^{-1} (on DM basis). Half of W(py) and control treatments were mixed with digestate (W(py)+D and C+D) before field application with an amount of 3.85 t ha^{-1} C corresponding to the digestate-C:biochar-C ratio of 1:2 of the fermented biochars. Cultivated crops were winter wheat (2012) and winter rye (2013) followed by the catch crop oil radish (*Raphanus sativus* var. *oleiformis*) (2014) and maize (2015). Each cultivation year, the N demand was examined and estimated at 150 kg N ha^{-1} for each crop. Mineral N fertilizer (Calcium ammonium nitrate, CAN 27% N) was applied in rates of 0%, 50%, 100% and 130%

of the estimated crop demand. Within cultivation period 2012-2015 sowing, harvest, soil cultivation, plant protection measures and N fertilization were performed according to Table 3. Meteorological data were taken from the weather station of German Meteorological Service located at the research station in Berge (
Figure 2).

[Table 2 near hear]

[Table 3 near hear]

Soil, biochar and digestate analysis

In 2012 soil samples (5 from each plot; crosswise sampling) were taken from fifteen evenly distributed plots to a depth of 10 cm to determine soil texture. Therefore, pipet method according to DIN ISO 11277 (2002) was applied after samples were air dried and sieved to 2 mm. For the interpolation of the particle size distribution over the entire experimental site the geographic information system (ArcGIS for Desktop 10.0, ESRI) using the *Local Polynomial Interpolation* method was applied. To determine the impact of biochar, digestate and mineral fertilizer N on total C (C_t) and total N (N_t) concentrations in the upper 20 cm of the soil, samples (five from each plot) were taken in 2012 before application of biochar, digestate and mineral N fertilizer, after winter wheat harvest (August 2013), after winter rye harvest (November 2014) and after the harvest of maize (September 2015). Samples were mixed to composite samples, respectively, and C_t and N_t were determined in duplicate by an elemental analyzer (Vario MAX Cube, Elementar Analysensysteme GmbH, Hanau, Germany)). The pH values, K_{dl} and P_{dl} were determined in 2012 before biochar application and in 2015 after maize harvest. Double lactate soluble P and K were analyzed according to the VDLUFA method (Naumann and Bassler 1991) and pH was measured potentiometrically. Samples for the determination of mineral N (N_{min}) were taken in 2012 before application of biochar, digestate and mineral N fertilizer and in 2015 after harvest of maize. Therefore, ammonium

(NH_4^+) and nitrate (NO_3^-) were extracted with 0.0125 M $CaCl_2$ (5ml per gram dry sample) and measured by flow-injection analysis (FIA System, MLE, Germany)

The DM and ash content of biochars and digestate were determined by drying for 24 h at 105 °C and subsequently at 550°C. Electric conductivity (EC) and pH values were measured in distilled water (ratio biochars/digestate and water; 1:2.5 w/v). Determination of N_{min} was performed using the same method like for soils. Sulphur (S), hydrogen (H), C and N was determined on an elemental analyzer (Vario EL III, Elementar Analysensysteme, Germany). Oxygen (O) contents were calculated using contents of C, H, N, S and ash contents. Total contents of calcium, iron, magnesium (Mg), potassium (K) and phosphorous (P) were determined by inductively coupled plasma optical emission spectrometry.

Crop yield and plant analysis

During growing seasons the growth and the development of winter wheat and maize was calculated on the basis of the BBCH-code (Meier 1997) whereas crop height was measured by a folding rule at five dates between May 2013 and June 2013 and June 2015 and September 2015. After harvest the fresh and dry matter of the winter wheat and winter rye straw and grain as well as the whole biomass of maize was determined. An aliquot of the wheat and rye straw and maize was dried at 60°C and milled to 1 mm to determine C and N by dry combustion on a Vario MAX CNS Element Analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). In the first year of cultivation an aliquot of wheat grains were also milled to 1 mm and analysed for C and N as described before. Contents of P K and Mg in grains were solubilized by microwave extraction (Mars 6, CEM, Germany) and analysed using an ICP-OES (Thermo, United States). With the N content of grains crude protein content was estimated (N×5.7), falling number (amylase activity index) (Perten 1964) and sedimentation value after ZELENY (Zabel 1965) were tested as proxy for the baking quality of wheat. The yield components were quantified during growing season by counting three times one meter ears for each plot and calculating ears per m^2. Grains per ear were also calculated by dividing ears per m^2 through grains per m^2. The thousand grain weight was determined on samples counted by a semi-automated counter. As a scale for the outer quality of wheat, the hectoliter weight was measured (Schmorl 1937).

Statistical analyses

Statistical analyses were performed using SAS software (SAS version 9.3; SAS Institute Inc., Cary, NC, USA), considering proxies for soil quality as covariates. Due to the fact, that the clay content varied across the experimental site (

Figure 3) and the distribution could not only be explained by the applied block design, we used the clay content as covariable in the statistical analyzes in addition to the block effect. In all models the considered covariate proved to be statistically different from zero. The models had a better fit (lower Akaike Information Criterion) than models without covariates. The data were grouped and evaluated according to the two OG's by two-way analysis of variance (ANOVA) with the main factors BC and D and the main factors BC and fN, respectively. The ANOVA were performed using *Proc Mixed* followed by *LSMeans Tukey* HSD post hoc test with significant effects considered for $P < 0.05$. The SAS macro *%MULT* was used to create a letter display representing the significant differences (Piepho 2012).

[Figure 1 near hear]

Results

Effects of W(py), M(py) and M(htc) treated with or without digestate (OG1)

Biochar application and digestate incorporation did not affect pH and P_{dl} whereas K_{dl} showed an interaction of BC and D in 2015 (Table 4) with a significant higher K_{dl} concentration solely in the control treatment amended with digestate (C+D_N150). Potassium contents in C+D_N150 were in the range of treatments amended with biochars; however, no further increase of K_{dl} was induced by digestate in biochar treatments. Three years after applying different biochars with or without digestate incorporation a significant effect of biochar application on soil C_t and N_t was detected. The application of M(htc) and W(py) resulted in significantly higher C_t concentrations in the upper 20 cm of the soil compared to control (Table 4). Carbon concentrations in W(py), M(htc), M(py) and control treatments were 11.2, 12.1, 9.8 and 9.3 g kg^{-1}. In the first and second year no impact of biochar and digestate on soil C_t could be detected. Similarly, no biochar effect was found for N_t between 2012 and 2014 whereas three years after biochar application N_t concentrations were also significantly higher in treatments with M(htc) and W(py) compared to control treatments (Table 4). Digestate incorporation also increased the soil C_t compared to control treatments after the third year of cultivation. However, in the first two years no digestate effect on C_t and on N_t could be proven (Table 4).

Concentrations of N_{min} measured in three soil depth (0-30, 30-60 and 60-90 cm) showed no significant differences at the initial state in 2012. In 2015, three years after biochar application, the total content of N_{min} in all treatments and layers were higher than in 2012. Also the allocation to the three layers (0-30, 30-60, 60-90cm) was different with 70%:20%:10% in 2012 and about 50%:30%:20% in 2015. Additionally, BC and D interacted significantly expressed in higher N_{min} contents in 30-60 cm depth solely in the M(py)+D_N150 treatment compared to all other treatments (Table 4).

[Table 4 near hear]

Yields of winter wheat, winter rye and maize showed no significant differences caused by BC or D compared to control treatments (Table 5). Averaged yields of winter wheat, winter rye and maize were 7.7 (grain) and 7.1 t ha^{-1} (straw), 8.1 (grain) and 8.3 t ha^{-1} (straw) and 13.8 t ha^{-1} (dry matter), respectively. During the vegetation period no differences in the plant-growth stages (BBCH-code; Meier (1997)) of winter wheat and maize and in growth heights of maize induced by biochar application or digestate incorporation were found. However, growth heights of winter wheat from May 2013 to June 2013 were significantly higher (2-4%)

in treatments with digestate incorporation. Thereafter, no statistically significant differences in heights of winter wheat were detected (data not shown). Plant-growth stages and heights of winter rye in 2013/2014 were not determined.

Total C and N contents in grain and straw of winter wheat and winter rye and total C content in maize biomass were not affected by BC or D. Solely N in maize biomass was significantly higher in digestate treatments but unaffected by BC (Table 5). Yield components of winter wheat had averaged amounts of 477, 34.3, 46.8 and 80.1 for ears m^{-2}, grains ear^{-1}, grain weight and hectoliter weight and showed no significant differences between biochar and digestate treatments, respectively. Similarly, the nutrient composition of wheat straw (except K_{straw}) showed no significant differences with average P_{straw} and Mg_{straw} contents of 0.69 and 0.64 g kg^{-1} dry soil, respectively. However, the K_{straw} content was significantly higher in treatments added with digestate independently of biochar addition (Table 6). The concentrations of P, K and Mg in wheat grain ranged between 4.0 – 4.7, 4.1 – 4.7 and 1.3 – 1.6 g kg^{-1}, respectively, and were significantly affected by the main factor BC. Phosphorus, K and Mg contents in grain had considerably higher contents in treatments with M(py) addition (Table 6). However, crude protein content ranged between 108 and 133 g kg^{-1} and was significantly positive affected by D, independently of biochar addition (Table 6). The falling number and the sedimentation value were on average 442 and 14.3, respectively, and no statistically significant impacts of the factor BC or D were found (Table 6).

Concerning the impact of different biochars treated with or without digestate no interactions of the main factors BC and D could be detected for any dependent variable (Table 4, 5 and 6).

[Table 5 near hear]

[Table 6 near hear]

Interaction of W(py) and mineral N fertilization (OG2)

To identify the interaction of biochar and mineral N fertilization, control and W(py) treatments without digestate incorporation, fertilized with 0, 75, 150 and 195 kg N ha^{-1}, respectively (Table 2) were considered. Similar to OG1, pH and plant available P was not affected by BC and fN three years after biochar application. However, plant available K showed an BC × fN interaction (Table 4) with a significant increase of K_{dl} in W(py) treatments compared to controls when fertilized with 75 and 150 kg N ha^{-1}. Total C concentration in the upper 20 cm of the soil was significantly higher in W(py) treatments compared to controls since the second year after biochar amendment (Table 4). In contrast, N_t concentrations were not significantly altered by W(py) within the entire field experiment. Mineral N measured in three soil depth (0-30, 30-60 and 60-90 cm) showed no significant differences in 2012. In 2015, N_{min} contents of control and W(py) treatments were higher compared to 2012 and increased significantly with increasing N rates (Table 4). Whereas about 70% of the N_{min} was found in the top 30 cm of the soil in 2012, the distribution of N_{min} after maize harvest was more homogenous to all three depths. In 2015, significantly higher N_{min} concentrations compared to controls were only found in treatments fertilized with 195 kg N ha^{-1} (Table 4), exclusively due to significantly different NO_3^-- N concentrations (data not shown).

Grain and straw yields of wheat and rye were significantly increased by mineral N fertilization compared to treatments with no mineral N addition (Table 5). Surprisingly, in the third year no impact of mineral N fertilization could be determined in maize yields. As already seen in OG1, the application of biochar, more precisely W(py), did not affect the yields over the three-year cultivation period. Also plant growth stages and growth heights of winter wheat were significantly affected by fertilizer N application rates. Growth heights measured in May and June 2013 increased with increasing N rates. At the End of June 2013 a BC × fN interaction was found with significant higher growth heights in W(py) treatments compared to controls when no N fertilizer was applied. The application of mineral N fertilizer accelerated the plant development. Whereas in fertilized treatments the flag leaf was already developed in May 2013, plants in control treatments were still in an earlier development stage. However, afterwards no further significant differences in plant growth stages were found. No effects of W(py) biochar on plant growth stages and growth heights of winter wheat were detected. During vegetation period of maize no differences in the plant-growth stages and in growth heights were induced by W(py) application or fertilizer N application rates.

Total C and N contents in grain and straw of winter wheat and winter rye and total N content in maize biomass were significantly higher in mineral N fertilized treatments (Table 6). A BC effect was not detected. All plant parameters, only determined for wheat in the first year, were significantly affected by the main factor fN, except grain weight. However, the effect of fertilizer N rates was different. For ears m^{-2}, grains ear^{-1}, hectoliter weight, K_{straw}, crude protein content and falling number highest values were determined at highest fertilizer N rates whereas for P_{straw}, Mg_{straw}, P_{grain}, K_{grain} and Mg_{grain} highest values were found in unfertilized/low fertilized treatments (Table 6). However, P_{grain} and falling number were additionally affected by W(py) application inducing increased values, but showed no interaction effects of BC and fN. For sedimentation value a BC × fN interaction effect was found, in that significant lower values occurred in treatments without biochar and fertilizer N addition. This means, that the addition of biochar or mineral N fertilizer, independent of the rate, induced significant higher sedimentation values compared to control treatments without biochar and N fertilizer addition. Statistically significant differences between biochar and N treatments could not be found (Table 6).

Discussion

Effects on yield components, quality and nutrients in winter wheat straw and grain

One year after biochar application we found statistically significant effects of biochar on crop quality and contents of specific chemical elements in the grain. The contents of P, K and Mg in winter wheat grain were significantly higher in M(py) treatments compared to the other biochars and the control presumably induced by highest contents of K and Mg and P in M(py) biochars (Table 1) due to the combination of feedstock (maize silage) and carbonization process (pyrolysis). Furthermore, the M(py) biochar could have affected the sorption and desorption of phosphate in the soil, resulting in higher uptake of P by the plants (Morales et al. 2013). Apparently P was not yield limiting in our study, since the additional availability of P did not affect crop yield. These findings contradicted the review of Singh et al. (2015) who stated that no impact of biochar on the crop nutritional quality took place during the initial time after application. Phosphate content of wheat grain as well as wheat quality was affected by both BC and fN. The higher P_{grain} contents in treatments applied with W(py) may also be induced by sorption desorption processes. On soils with low concentration of available P biochar obtained by pyrolysis might have the potential to reduce P fertilizer demand. Also, the indicator for wheat quality falling number was positively affected by BC. However, falling numbers >300 sec indicate a reduced enzyme activity and therefore low baking quality, which possibly could be explained by a rather late harvest date of the wheat.

The K content in straw (K_{straw}) was significantly affected by digestate addition. A reason for that could be the high K content in digestate and biochars with digestate incorporation and subsequent fermentation (Table 1) which also increased K content in soil. A higher K_{straw} content in treatments with the same digestate and biochars was also found in a pot experiment with spring wheat (Reibe et al. 2014). Similarly, crude protein content of winter wheat grain showed highest values in digestate treatments. As the crude protein content is mainly influenced by fN (Ozturk et al. 2003), the high content of available N (102 mg NO_3^--N kg^{-1}, 253 mg NH_4^+-N kg^{-1}; Table 1) in the digestate might have been the reason for this effect.

Biochar application induced no effects on yield components such as ears m^{-2}, grains ear^{-1}, grain weight and hectoliter weight. This result was also consistent over the four different fertilizer levels as well as for digestate incorporation. This is in line with results after an application of spruce and pine-biochar in a field experiment with winter wheat in Finland in the first year (Tammeorg et al. 2014a).

Effects on yield and plant growth

Even though the contents of nutrients important for plant growth (K, P, Mg) were increased in the first year after biochar application, no effect on crop yields within three years were detected. This could be explained by an already good supply of K and P in the initial soil. Similar results regarding the neutral yield effects were reported from other perennial field studies performed under temperate and boreal conditions for a variety of crops, as spring barley (Nelissen et al. 2015), maize (Jones et al. 2012, Borchard et al. 2014), wheat, turnip rape and faba bean (Tammeorg et al. 2014a, Tammeorg et al. 2014b). Apparently in the temperate zones yield response to biochar is not as pronounced as in tropical environments.

The positive effects of mineral N fertilizer on crop yields are already well known. Our results showed no interaction effects of biochar and mineral N fertilizer. In contrast, Chan et al. (2007) found significant BC × fN interaction effects in a study with 10, 50 and 100 t biochar ha^{-1} and 100 kg N ha^{-1} N fertilization showing increasing yields with increasing rates of biochar application in the presence of N fertilizer. The application rate of biochar in our study was in the lower range of that in the above mentioned one, which may explain the limited response to interaction effects. However, at agricultural field scale biochar application rates of 50 t ha^{-1} and above are economically not feasible. Usually, the positive effects of mineral N fertilizer on crop yields are also applicable for maize. However, in our study neither mineral N fertilizer nor biochar or digestate application affected the yield of maize probably due to a sufficient availability of N from soil N. One explanation might be an established surplus of N after ploughing the oil radish, which was cultivated before maize. Because of this also the unfertilized controls as well as the lower fertilized plots received sufficient N. Another possible explanation could be a shift of mineral N into deeper soil layers or removal through surface runoff directly after application because of an exceptionally high precipitation event directly after the first fertilization in May (

Figure 2). An indication for this is the higher soil N_{min} status after maize harvest compared to 2012 and a higher proportion of N_{min} in deeper soil layers (30-90 cm) (Table 4).

Significantly higher crop heights of winter wheat from May 2013 to June 2013 induced by digestate incorporation could be explained by an input of plant available nutrients (Mg, Ca, K etc.) within digestate. Schulz and Glaser (2012) observed a similar effect of biochar amended with compost on the crop height of oat.

[

Figure 2 near hear]

Effects on soil C content

Biochars are C rich products which mainly consist of aromatic compounds and therefore are suitable to sequester C in agricultural soils (Lehmann and Joseph 2009). Most studies observed an increase of soil C directly and also several years after the application of biochar (Chan et al. 2007, Biederman and Harpole 2013, Liu et al. 2014, Nelissen et al. 2015). In this study we detected statistically significant changes of C_t concentrations in the first two years only for W(py) biochar addition in OG2, however, not in OG1 when comparing W(py) with the other biochars and the control. One explanation for not finding a statistical proof for added C in OG1 is probably related to the high variance of C_t among the replications, which is about twice as high as the variance of the control treatments. Furthermore, due to the experimental design the statistical analysis of the factor biochar (W(py)) in OG2 were based on twice the observations compared to OG1. However, M(py) and M(htc) were only investigated in OG1. Hence, the results cannot certainly contribute to the question of potential

C mineralization of biochar or soil C of the treatments M(py) and M(htc). However, the significant increase of C_t concentration after W(py) application indicate the potential of pyrolyzed wood-biochar to sequester C after application to soil. This might have been a result of the low hydrogen (H):C ratio (Table 1) of W(py). The H:C ratio as well as the oxygen (O):C ratio are regarded as indicators for the aromaticity and stability of biochars (Lehmann and Joseph 2009, Spokas et al. 2011). Likewise, the high pyrolysis temperature and C_t content of the W(py) biochar suggests lower biochar mineralization rates due to a higher degree of aromaticity and stability (Ameloot et al. 2013). The H:C ratio and C_t content of M(py) was approximately as high as in W(py) but induced minor changes in soil C_t compared to W(py). Possibly, due to the higher N content in M(py) microbial activity was increased in these treatments simultaneously inducing a priming effect in these treatments. Hydrothermal carbonization as well as the addition of digestate by subsequent fermentation resulted in increased H:C and O:C ratios and reduced C_t contents (Table 1), respectively, indicating a reduced stability and therefore a diminished ability to sequester C of these biochars. After the third year of cultivation, significantly higher C_t and N_t concentrations were also observed in M(htc) treatments compared to controls, however, exclusively in treatments where biochar was fermented with digestate. Possibly, M(htc) and digestate developed an interaction which increased the soil C content by stabilizing the biochar-C or enhancing the microbial biomass. These increases of C_t indicated the potential of pyrolyzed and hydrothermal carbonized biochar to sequester C after application to soil. However, it also showed that not only the type of carbonization method or feedstock caused this effect.

Conclusion

After the application of differently produced biochars based on biomass of wood debris and maize, crop yields of winter wheat, winter rye and maize were not affected by biochar and showed no interaction effects with N fertilizer supply. This result limits the potentials of biochar for sustainable intensification and reduced environmental damage due to agricultural production for the temperate zones. The presented results indicated that the different biochars may induce improved availability of plant nutrients in the first year after application to a temperate sandy soil. This was shown by higher contents of plant nutrients in the winter wheat straw and grain, however, without positive yield response. Apparently, these plants nutrients were not yield limiting in our case. Yet, it has to be mentioned that the biochar application rates in this study were comparatively low. The incorporation of digestate by fermentation or mixing showed no yield effect but positively affected the soil nutrient content in combination with the biochars. However, the fact that no negative yield effects were found after biochar application suggests the potential of biochar for C sequestration and other environmental benefits, which still need to be identified.

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Table 1. Biochar and digestate characteristics

		D	W(py)	M(py)	M(py)+D	M(htc)	M(htc)+D
$DM_{105°C}$	(g kg FM^{-1})	236	551	929	300	474	328
Ash	(g kg DM^{-1})	343	166	184	276	32	252
pH	($CaCl_2$)	8.26	9.35	9.89	9.52	5.25	7.03
EC	(Sm^{-1})	2.38	1.71	3.08	2.25	0.30	1.24
NH_4^+-N	(mg kg^{-1} DM)	253	0.64	2.59	13.9	0.39	49.25
NO_3^--N	(mg kg^{-1} DM)	102	0.88	1.27	41.78	n.d.	1.20
N_t	(g kg^{-1} DM)	36.6	7.19	16.5	25.8	20.9	28.8
C_t	(g kg^{-1} DM)	401	776	752	558	646	549
S_t	(g kg^{-1} DM)	5.36	2.47	2.67	4.00	2.88	3.36
H_t	(g kg^{-1} DM)	40.4	14.0	13.4	24.2	46.0	56.8
O	(g kg^{-1} DM)	174	33.7	31.6	113	253	110
H/C	atomic ratio	1.21	0.22	0.21	0.52	0.86	1.24
O/C	atomic ratio	0.33	0.03	0.03	0.15	0.29	0.15
Ca	(g kg^{-1} DM)	14.27	26.23	9.62	17.04	2.71	7.30
Fe	(g kg^{-1} DM)	3.67	3.08	11.81	13.70	3.69	3.90
Mg	(g kg^{-1} DM)	3.12	3.05	5.11	4.57	0.43	1.33
K	(g kg^{-1} DM)	20.01	5.77	33.53	25.40	1.22	8.11
P	(g kg^{-1} DM)	4.14	2.26	5.67	8.07	2.16	2.93

DM dry matter, *EC* electrical conductivity, N_t total nitrogen, C_t total carbon, S_t total sulfur, H_t total hydrogen, *O* oxygen, *Ca* calcium, *Fe* iron, *Mg* magnesium, *K* potassium, *P* phosphorous, *D* digestate, *W* pyrolyzed wood, *M(py)* pyrolyzed maize silage, *M(py)+D* fermented pyrolyzed maize silage, *M(htc)* hydrothermal carbonized maize silage, *M(htc)+D* fermented hydrothermal carbonized maize silage, *n.d.* not detectable

Table 2. Treatments and factors of the field experiment as well as the assignment to the orthogonal groups.

Treatment	Factors: BC feedstock	Factors: BC process	Factors: D	Factors: fN [kg N ha^{-1}]	Orthogonal groups: OG 1	Orthogonal groups: OG2	Total amount of biochar and digestate [t DM ha^{-1}]
C-D_N0	-	-	-	-		x	-
C-D_N75	-	-	-	75		x	-
C-D_N150	-	-	-	150	x	x	-
C-D_N195	-	-	-	195		x	-
C+D_N150	Maize silage	Anerobic digestion	added on the field	150	x		9.6
W(py)-D_N0	Wood	Pyrolysis	-	-		x	10
W(py)-D_N75	Wood	Pyrolysis	-	75		x	10
W(py)-D_N150	Wood	Pyrolysis	-	150	x	x	10
W(py)-D_N195	Wood	Pyrolysis	-	195		x	10
W(py)+D_N150	Wood+Maize silage	Pyrolysis+Anerobic digestion	added on the field	150	x		10+9.6
M(py)-D_N150	Maize silage	Pyrolysis	-	150	x		10
M(py)+D_N150	Maize silage	Pyrolysis+Anerobic digestion	by fermentation	150	x		14
M(htc)-D_N150	Maize silage	Hydrothermal carbonization	-	150	x		12
M(htc)+D_N150	Maize silage	Hydrothermal carbonization+Anerobic digestion	by fermentation	150	x		14

C control, *W* wood, *M* maize, *py* pyrolyzed, *htc* hydrothermal carbonized, *D* digestate, *BC* biochar, f*N* fertilizer N rates, *DM* dry matter, *x* treatment belongs to the Orthogonal Group above-named

Table 3. Agro-technical data

Management	Date
Application of biochars and digestate	12-Sep-2012
Tillage with cultivator	17-Sep-2012
Tillage with plow	20-Sep-2012
Crop: Winter wheat (*Triticum aestivum* L.)	
Sowing (350 seeds m^{-2})	18-Oct-2012
Herbicide application (3 l ha^{-1} Picona)	12-Nov-2012
1. Mineral fertilization	11-Apr-2013
2. Mineral fertilization	6-May-2013
Fungicide application (1 l ha^{-1} Juwel Top)	14-May-2013
Fungicide application (0.5 l ha^{-1} Taspa)	4-Jun-2013
Insecticide application (0.075 l ha^{-1} Karate Zeon)	4-Jun-2013
Harvest	15-Aug-2013
Stubble mulching	22-Aug-2013
Tillage with cultivator	27-Aug-2013
Tillage with cultivator	17-Sep-2013
Tillage with plow	24-Sep-2013
Crop: Winter rye (*Secale cereale* L.)	
Sowing (150 seeds m^{-2})	25-Sep-2013
Herbicide application (5 l ha^{-1} Boxer, 0.07 l ha^{-1} Primus)	25-Oct-2013
Growth regulator application (0.8 l ha^{-1} CCC)	25-Oct-2013
1. Mineral fertilization	6-Mar-2014
Herbicide application (50 g ha^{-1} Artus, 0.1 l ha^{-1} Primus)	14-Mar-2014
Fungicide application (0.9 l ha^{-1} Champion)	14-Mar-2014
2. Mineral fertilization	14-Apr-2014
Fungicide application (0.9 l ha^{-1} Diamant)	14-May-2014
Harvest	7-Aug-2014
Tillage with disc harrow	12-Aug-2014
Sowing of oil radish (*Raphanus sativus* var. *oleiformis*)	3-Sep-2014
Tillage with disk harrow	21-Apr-2015
Crop: Maize (*Zea mays* L.)	
Sowing (16 seeds m^{-2})	22-Apr-2015
1. Mineral fertilization	11-May-2015
Herbicide application (1.5 l ha^{-1} Calaris)	20-May-2015
Fungicide application (1.25 l ha^{-1} Diamant)	20-May-2015
Herbicide application (0.7 l ha^{-1} Motivell Forte)	20-May-2015
2. Mineral fertilization	16-Jun-2015
Herbicide application (2 l ha^{-1} Gardow Gold)	16-Jun-2015
Harvest	18-Sep-2015

Table 4. Soil pH, double lactate soluble P (P_{dl}) and potassium (K_{dl}), total carbon (C_t) and nitrogen (N_t) and mineral N (N_{min}) contents in soil and the probability values for the treatment factors biochar and digestate incorporation/fermentation and their interactions in the first orthogonal group as well as for the treatment factors biochar and N-fertilization and their interactions in the second orthogonal group.

		pH		K_{dl}		P_{dl}		C_t				N_t				N_{min} 2012			N_{min} 2015		
		2012	2015	2012	2015	2012	2015	2012	2013	2014	2015	2012	2013	2014	2015	0-30 cm	30-60 cm	60-90 cm	0-30 cm	30-60 cm	60-90 cm
		(-)		(mg 100g^{-1})		(mg 100g^{-1})		(g kg^{-1})				(g kg^{-1})				(kg ha^{-1})			(kg ha^{-1})		
OG1																					
C		6.12	6.29	11.4	16.1	5.80	5.51	7.39	9.19	8.81	9.34 c	0.69	0.82	1.01	0.61 b	39.5	9.7	4.20	63.4	37.4 b	16.8
M(py)		5.81	6.08	8.85	19.6	4.89	5.18	7.16	9.51	9.77	9.82 bc	0.64	0.79	0.87	0.61 b	47.9	13.2	4.50	63.4	76.9 a	23.1
M(htc)		5.93	6.15	13.1	17.9	5.25	5.79	7.37	9.61	9.53	12.1 a	0.70	0.80	0.90	0.77 a	37.0	12.2	4.92	60.4	31.3 b	16.1
W(py)		5.81	6.15	10.5	17.5	4.44	5.38	7.16	10.6	10.0	11.2 ab	0.66	0.80	0.91	0.67 ab	40.8	10.8	4.63	57.3	42.5 ab	17.8
D_no		5.88	6.15	10.0	16.6 b	4.93	5.39	7.07	9.36	9.03	10.1 b	0.66	0.77	0.84	0.62	39.5	12.4	4.20	50.8	34.5 b	16.1
D_yes		5.95	6.18	11.8	19.0 a	5.26	5.53	7.29	10.1	10.0	11.1 a	0.68	0.84	1.01	0.70	43.1	10.5	4.93	71.4	59.5 a	20.8
	df	*P*-values																			
BC	3	0.326	0.690	0.228	0.122	0.532	0.606	0.939	0.121	0.110	**0.0004**	0.873	0.941	0.893	**0.025**	0.369	0.591	0.817	0.964	**0.017**	0.387
D	1	0.555	0.796	0.138	**0.021**	0.612	0.669	0.468	0.180	0.068	**0.024**	0.543	0.157	0.071	0.063	0.550	0.314	0.209	0.236	**0.016**	0.207
BC x D	3	0.895	0.378	0.341	**0.009**	0.520	0.900	0.532	0.071	0.575	0.711	0.691	0.702	0.565	0.743	0.288	0.485	0.753	0.605	**0.024**	0.165
OG2																					
C		6.15	6.36	12.0	13.6 b	5.75	5.57	7.63	8.94	8.09 a	9.20 b	0.70	0.80	0.82	0.62	40.0	9.9	4.1	57.9	27.9	17.9
W(py)		5.93	6.24	10.6	16.7 a	5.14	5.39	7.26	9.72	9.78 b	10.2 a	0.66	0.76	0.83	0.60	41.6	11.2	6.8	40.8	32.1	15.9
N0		5.84	6.31	10.6	14.5	5.49	5.59	6.96	9.06	7.91	9.27	0.64	0.76	0.76	0.56	42.2	10.4	4.08	19.6 b	14.5 b	13.9 b
N75		6.11	6.46	11.8	15.0	5.84	5.66	7.49	9.10	10.0	9.84	0.68	0.79	0.85	0.63	44.7	11.8	9.47	23.5 b	17.5 ab	14.3 b
N150		5.95	6.24	9.5	14.9	4.61	5.48	7.19	9.14	8.60	9.66	0.66	0.76	0.82	0.60	38.2	10.1	3.91	59.0 ab	35.0 ab	16.9 b
N195		6.26	6.20	13.3	16.1	5.83	5.20	8.13	10.0	9.24	10.1	0.74	0.81	0.88	0.66	38.1	10.0	4.29	95.13 a	53.0 a	22.8 a
	df	*P*-values																			
BC	1	0.229	0.260	0.332	**<.0001**	0.211	0.586	0.834	0.144	**0.004**	**<.0001**	0.919	0.722	0.707	0.412	0.730	0.483	0.271	0.264	0.960	0.075
fN	3	0.408	0.307	0.152	0.851	0.262	0.859	0.498	0.484	0.163	0.928	0.877	0.929	0.083	0.877	0.773	0.699	0.442	**0.005**	**0.032**	**0.0002**
BC x fN	3	0.715	0.317	0.505	**0.007**	0.082	0.557	0.617	0.435	0.525	0.358	0.627	0.603	0.569	0.376	0.838	0.556	0.512	0.540	0.902	0.371

C Control, *M(py)* pyrolyzed maize silage, *M(htc)* hydrothermal carbonized maize silage, *W(py) pyrolyzed* wood, *D* digestate, *BC* biochar, fN fertilizer N rates, N0 0 kg N ha^{-1}, N75 75 kg N ha^{-1}, N150 150 kg N ha^{-1}, N195 195 kg N ha^{-1}, df degrees of freedom. Data shown are means (4 replicates across 4 treatment levels for BC in OG1, 2 treatment levels for BC in OG2, 2 treatment levels for D and 4 treatment levels for N). Different letters indicate significant differences (p<0.05) between treatments. The significant (p<0.05) main factor P values are bolded.

Table 5. Crop yields and carbon (C) and nitrogen (N) in plants over the experiment runtime and the probability values for the treatment factors biochar and digestate incorporation/fermentation and their interactions in the first orthogonal group as well as for the treatment factors biochar and N-fertilization and their interactions in the second orthogonal group.

		winter wheat yield		winter rye yield		maize yield	winter wheat				winter rye				maize	
		grain	straw	grain	straw	biomass	grain		straw		grain		straw		biomass	
		(t ha^{-1})		(t ha^{-1})		(t ha^{-1})	C (t ha^{-1})	N (t ha^{-1})	C (t ha^{-1})	N (t ha^{-1})	C (t ha^{-1})	N (t ha^{-1})	C (t ha^{-1})	N (t ha^{-1})	C (t ha^{-1})	N (t ha^{-1})
OG1																
C		7.92	7.00	8.29	7.89	13.6	3.10	0.15	2.81	0.03	3.22	0.12	3.19	0.05	6.84	0.21
M(py)		7.62	7.05	8.15	7.93	13.7	2.61	0.13	2.85	0.02	3.17	0.13	3.22	0.05	6.79	0.20
M(htc)		7.42	6.99	8.35	8.26	13.9	2.91	0.14	2.83	0.02	3.26	0.13	3.36	0.05	7.01	0.21
W(py)		7.76	7.55	8.22	8.14	13.9	3.06	0.15	3.05	0.03	3.17	0.13	3.31	0.05	6.88	0.21
D_no		7.53	7.02	8.20	7.90	13.6	2.95	0.14	2.84	0.02	3.20	0.12	3.21	0.05	6.81	0.20 b
D_yes		7.85	7.27	8.30	8.21	13.9	2.89	0.14	2.93	0.02	3.22	0.13	3.33	0.05	6.95	0.21 a
	df								*P*-values							
BC	3	0.560	0.119	0.714	0.721	0.889	0.420	0.323	0.124	0.373	0.628	0.976	0.589	0.258	0.808	0.522
D	1	0.259	0.292	0.490	0.245	0.412	0.721	0.797	0.339	0.303	0.675	0.379	0.589	0.424	0.417	**0.020**
BC x D	3	0.795	0.408	0.113	0.650	0.195	0.425	0.387	0.394	0.994	0.086	0.074	0.674	0.731	0.373	0.323
OG2																
C		6.42	6.41	7.54	7.11	13.6	2.43	0.11	2.56	0.02	2.93	0.10	2.86	0.04	6.80	0.19
W(py)		6.64	6.58	7.58	7.18	13.6	2.34	0.11	2.64	0.02	2.93	0.11	2.90	0.04	6.76	0.18
N0		3.77 c	3.88 b	6.10 b	5.34 b	13.2	1.15 b	0.05 b	1.52 c	0.009 c	2.37 b	0.08 c	2.11 b	0.02 c	6.53	0.14 b
N75		6.46 b	6.39 a	7.98 a	7.46 a	13.9	2.53 a	0.11 a	2.56 b	0.016 b	3.09 a	0.10 b	3.00 a	0.03 b	7.04	0.20 a
N150		7.74 a	7.32 a	8.22 a	7.98 a	13.7	3.04 a	0.15 a	2.95 a	0.024 a	3.19 a	0.12 a	3.17 a	0.05 a	6.85	0.20 a
N195		8.14 a	7.89 a	7.92 a	7.79 a	13.6	2.82 a	0.14 a	3.17 a	0.031 a	3.07 a	0.12 a	3.24 a	0.05 a	6.70	0.21 a
	df								*P*-values							
BC	1	0.286	0.122	0.987	0.699	0.735	0.892	0.666	0.095	0.581	0.925	0.979	0.578	0.224	0.645	0.150
fN	3	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.379	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	**<.0001**	0.095	**<.0001**
BC x fN	3	0.817	0.281	0.066	0.881	0.345	0.626	0.524	0.291	0.617	0.052	0.297	0.914	0.847	0.396	0.620

C Control, *M(py)* pyrolyzed maize silage, *M(htc)* hydrothermal carbonized maize silage, *W(py) pyrolyzed* wood, *D* digestate, *BC* biochar, *fN* fertilizer N rates, *N0* 0 kg N ha^{-1}, *N75* 75 kg N ha^{-1}, *N150* 150 kg N ha^{-1}, *N195* 195 kg N ha^{-1}, *df* degrees of freedom. Data shown are means (4 replicates across 4 treatment levels for BC in OG1, 2 treatment levels for BC in OG2, 2 treatment levels for D and 4 treatment levels for N). Different letters indicate significant differences ($p<0.05$) between treatments. The significant ($p<0.05$) main factor P values are bolded.

Table 6. Yield components of wheat, plant analysis of wheat straw and grain and the quality of wheat grains and the probability values for the treatment factors biochar and digestate incorporation/fermentation and their interactions in the first orthogonal group as well as for the treatment factors biochar and N-fertilization and their interactions in the second orthogonal group.

		Ears m^{-2} (-)	Grains ear^{-1} (-)	Thousand grain weight (g)	Hectolitre weight (kg hl^{-1})	P_{straw} (g kg^{-1})	K_{straw} (g kg^{-1})	Mg_{straw} (g kg^{-1})	P_{grain} (g kg^{-1})	K_{grain} (g kg^{-1})	Mg_{grain} (g kg^{-1})	Crude protein content (% DM)	Falling number (-)	Sedimentation value (-)
OG1														
C		453	37.9	46.6	80.2	0.69	8.06	0.64	4.13 b	4.19 b	1.30 b	128	436	14.0
M(py)		474	31.9	47.2	80.0	0.71	7.79	0.66	4.44 a	4.48 a	1.43 a	127	436	14.5
M(htc)		504	31.5	47.2	80.1	0.66	7.77	0.62	4.15 b	4.22 ab	1.32 b	125	442	14.3
W(py)		477	35.8	46.4	80.1	0.70	8.05	0.65	4.16 b	4.20 ab	1.29 b	121	454	14.5
D_no		479	34.3	46.7	80.1	0.65	7.57 b	0.65	4.21	4.31	1.34	121 b	438	14.3
D_yes		475	34.3	46.9	80.2	0.73	8.26 a	0.64	4.22	4.23	1.33	130 a	446	14.4
	df							*P*-values						
BC	3	0.613	0.052	0.439	0.598	0.963	0.797	0.842	**0.016**	**0.025**	**0.007**	0.555	0.156	0.303
D	1	0.874	0.998	0.675	0.437	0.165	**0.023**	0.702	0.888	0.250	0.510	**0.002**	0.244	0.625
BC x D	3	0.647	0.097	0.703	0.689	0.705	0.384	0.968	0.423	0.851	0.499	0.754	0.391	0.134
OG2														
C		461	29.3	45.9	79.6	0.72	7.70	0.68	4.15 b	4.28	1.36	11.8	407 b	12.5 b
W(py)		456	28.9	45.9	79.5	0.73	7.73	0.68	4.33 a	4.41	1.39	12.0	430 a	14.3 a
N0		389 b	18.6 b	45.2	79.0 b	0.96 a	7.21 b	0.77 a	4.45 a	4.48 ab	1.50 a	11.0 b	392 b	11.5 b
N75		443 ab	31.3 a	46.9	79.5 ab	0.57 c	7.13 b	0.64 b	4.30 ab	4.52 a	1.43 a	10.9 b	400 b	13.6 a
N150		477 a	35.9 a	46.2	80.0 a	0.64 bc	7.80 ab	0.65 b	4.12 ab	4.24 ab	1.30 b	12.4 a	436 a	14.0 a
N195		525 a	30.6 a	45.5	79.7 ab	0.73 b	8.71 a	0.67 ab	4.09 b	4.15 b	1.28 b	13.3 a	446 a	14.6 a
	df							*P*-values						
BC	1	0.842	0.857	0.997	0.512	0.763	0.890	0.938	**0.048**	0.164	0.317	0.666	**0.013**	**<0.001**
fN	3	**0.002**	**0.0004**	0.068	**0.018**	**<.0001**	**0.0003**	**0.010**	**0.025**	**0.019**	**0.0001**	**<.0001**	**<0.001**	**<0.001**
BC x fN	3	0.952	0.569	0.780	0.844	0.556	0.259	0.306	0.108	0.277	0.210	0.684	0.656	**0.003**

C Control, *M(py)* pyrolyzed maize silage, *M(htc)* hydrothermal carbonized maize silage, *W(py) pyrolyzed* wood, *D* digestate, *BC* biochar, *fN* fertilizer N rates, *N0* 0 kg N ha^{-1}, *N75* 75 kg N ha^{-1}, *N150* 150 kg N ha^{-1}, *N195* 195 kg N ha^{-1}, *df* degrees of freedom, P_{straw} phosphorous in straw, K_{straw} potassium in straw, Mg_{straw} magnesium in straw, P_{grain} phosphorous in grain, K_{straw} potassium in grain, Mg_{straw} magnesium in grain. Data shown are means (4 replicates across 4 treatment levels for BC in OG1, 2 treatment levels for BC in OG2, 2 treatment levels for D and 4 treatment levels for N). Different letters indicate significant differences (p<0.05) between treatments. The significant (p<0.05) main factor P values are bolded.

Figure captions

Figure 1. Design of the field experiment and the division of one plot

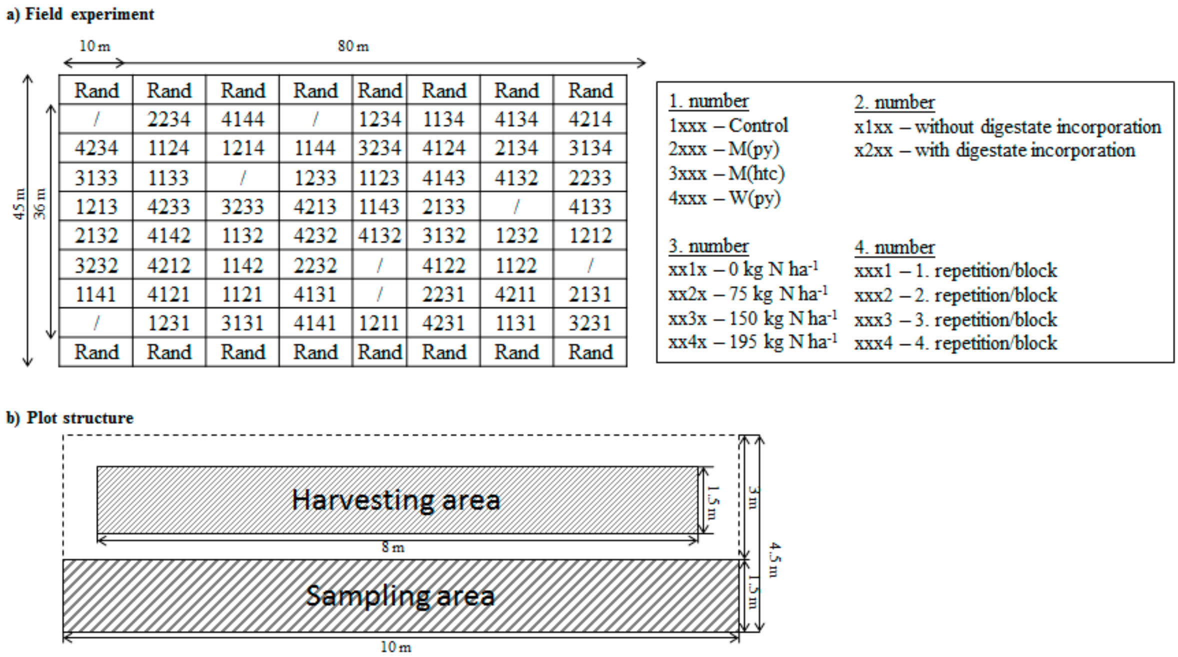

Figure 2. Air temperature, precipitation and time of fertilization during maize cultivation.

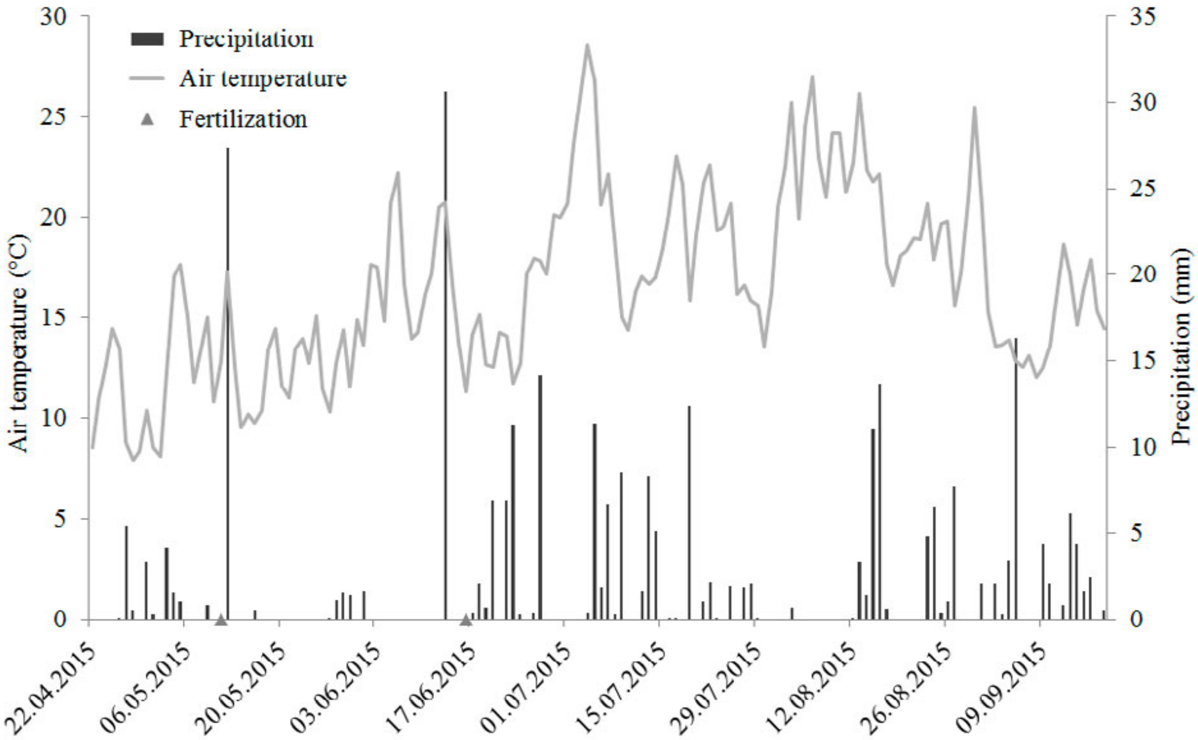

Figure 3. Clay content across experimental area.