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Biochar application to temperate soils: effects on nutrient uptake and crop yield under field conditions

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The benefits of biochar (BC) application to fertile, non-acidic soils in temperate climate regions might not always be as evident as for highly weathered tropical soils. The aim of our study was to investigate the effects of BC on soil characteristics, nutrient uptake and crop yield in field experiments on two temperate soils (Cambisol and Chernozem) in Austria. Maize and wheat (Cambisol), and barley and sunflower (Chernozem) were grown in successive vegetation periods following different BC application rates (0, 24 and 72 t ha^{-1} at the start of the experiment), supplemented with identical mineral N supply in 33 m² plots. BC treatments showed varying impacts on nutrient uptake of the investigated crops. The first growing season in the Chernozem region was affected by a prolonged drought period, which resulted in positive effects of BC on soil water-holding capacity (WHC) and barley crop yield (+ 10%) for the 72 t ha^{-1} BC + N treatment compared to a control with identical nutrient supply but without BC. However, maize and wheat grain yield decreased by 46 and 70%, respectively, after the highest BC application rate (72 t ha^{-1}) in an additional treatment without supplementary N-fertilisation. Still, even with high BC application rates we did not observe any adverse effects on crop yield and nutrient uptake, as long as the soil was supplied with sufficient N according to local agricultural practice.

Key words: Soil amendment, soil fertility, water-holding capacity, wheat, barley, maize, sunflower

Acronyms and abbreviations

BC	biochar
BD	bulk density
DM	dry mass
EC	electrical conductivity
CAL	calcium acetate lactate
CEC	cation exchange capacity
NPK	nitrogen (N), phosphorus (P), potassium (K)
NSP	nitrogen supplying potential
SOM	soil organic matter
PAW	plant available water
SD	standard deviation
WHC	water-holding capacity

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Introduction

The interest in biochar (BC) has extended from the effects on tropical soils to the potential of BC as a soil management strategy for global agriculture. After Terra Preta (Terra Preta de Indio, Portuguese for black earth) has been identified in the Amazon region in the 19^{th} century, it has been studied by naturalists, archaeologists and pedologists (da Costa et al. 2004). Terra Preta is classified as a fertile soil in an infertile surrounding, containing high concentrations of nutrients and stable soil organic matter (SOM) (Lehmann et al. 2003). The high amounts of SOM were caused by large inputs of domestic waste and black carbon that had formed due to natural and anthropogenic burning activities; therefore, up to 70 times more black carbon can be found in Terra Preta soils compared to the surrounding soils in the Amazon (Glaser et al. 2002, Novotny et al. 2009). These observations helped to create the hypothesis that the application of black carbon as pyrolysed biomass would increase the soil fertility of any agricultural soil. However, such a hypothesis is not self-evident and requires experimental confirmation.

Pyrolysis of biomass leads to the formation of the solid product BC that, upon application to the soil, may play an important role as a carbon sink and soil amendment. Among the potential benefits of BC for soil, the slow release of plant macronutrients contained in the BC is considered as a possibility to reduce the need for fertilisers in agriculture (Zheng et al. 2013a). Turning biomass into BC, oil and syngas by pyrolysis may even be carbon negative, if the syngas is used for energy purposes (Lehmann 2007, Goldberg 1985, Kuhlbusch and Crutzen 1995, Pramod et al. 2010, Ippolito et al. 2012).

In addition to C sequestration in the soil, BC comprises intrinsic properties that may make BC suitable as a soil amendment. A number of studies on different BC types and pyrolysis temperatures revealed that BC may induce a liming effect in the soil with a concomitant increase in cation exchange capacity (CEC). Further, BC can also lead to increased water and nutrient holding capacity (Gaskin et al. 2008, Singh et al. 2010, Gaskin et al. 2010, Uzoma et al. 2011, Kloss et al. 2012, 2013).

The particular effects of BC application on soil and plant yield, however, are not only dependent on the quality of the BC, but also on the specific soil characteristics (e.g. soil texture, SOM, pH). Most of the pot and field experiments that have been carried out were related to highly weathered, nutrient-poor tropical soils, as assorted in the reviews by Glaser et al. (2002), Blackwell et al. (2009) and Sohi et al. (2010). In the relevant studies, positive effects on both, soil and plants, were found, which might partly be attributed to a reduction of Al toxicity in the rhizosphere, as a result of the increase in pH (Kuka et al. 2013, Yang et al. 2013). However, the same effects may not be conferrable to other climatic regions with different soil types (Major et al. 2010) and, thus, require separate investigations. Studies that have been performed in temperate regions indicated that BC may cause only small, transient or even unwanted effects on soil and plant yield (Jones et al. 2012, Gaskin et al. 2010, Rajkovich et al. 2012, Kloss et al. 2013, Quilliam et al. 2012). Güereña et al. (2013) applied up to 30 t ha^{-1} BC in a North American temperate region, in a soil with sufficiently high native fertility. In their study, maize yield was within the current average yields of this region and hence, Güereña et al. (2013) suggest that specific soil productivity constraints have to be identified before BC application.

Asai et al. (2009) reported that the usage of BC without any further N fertiliser tended to decrease crop yield in soils with a low indigenous N supply. On the other hand, BC application in temperate regions may have other positive effects on the soil, which must not be disregarded. For example, Jeffery et al. (2011) concluded in a meta-analysis that BC application to medium and coarse textured soils increased soil WHC. The magnitude of this effect was found to be influenced by the respective soil characteristics. Atkinson et al. (2010) found that sandy soils were likely to have greater benefits from BC than clayey soils. They assumed that increased WHC of a soil (after BC application) was caused by a change in pore-size distribution and subsequently altered percolation patterns and flow paths. Liu et al. (2012) found synergetic positive effects of BC and compost in their field experiment in a sandy soil in Germany. Soil fertility and plant available water-holding capacity significantly increased after the compost-BC mixtures.

Detailed investigations of the effects of BC application on agricultural soils in temperate regions are crucial to better understand the potential of BC to increase soil fertility and to raise yields in soils outside of subtropical and tropical regions that are neither nutrient-deficient nor acidic. Therefore, this study had the objective to analyse the effects of a wood-derived BC on the crop yields in two representative agricultural soils in Central Europe over two years. Additionally, investigations of the effects on physico-chemical properties of the soils and on nutrient uptake of the crop plants should illuminate possible mechanisms for either positive or adverse yield effects of BC applications.

Materials and methods

BC characterisation

Beech wood BC from S.C ROMCHAR S.R.L (Romania) was added at rates of 30 t ha^{-1} and 90 t ha^{-1} fresh mass, respectively, once at the start of the experiment. After correction for the 20% water content, the BC application rates amounted to 24 and 72 t ha^{-1} (Table 1). Representative samples from the BC used as additive at both field experiments were taken with n=3. The material was dried at 47 °C until weight stability. The results of the BC water content determinations were in close agreement with the specifications of the BC producer. The BC was a wood-based slow pyrolysis product (550 °C; < 2 cm) with a pH of 9.0, 80% C, 1.6% H, 0.4% N, a H/C$_{org}$ ratio of 0.3 and a PAH content (∑ 16 EPA PAH) of 9 mg kg^{-1}. Concentrations of heavy metals amounted to (in mg kg^{-1}): Cd <0.2, Cr 51, Cu 16, Pb 2, Zn 93, As <0.8, Ni 8, Tl <0.2 and Hg <0.07.

Study sites

The two study sites are located in Lower Austria and Styria, Austria. The soil in Traismauer, Lower Austria (48°19’52.6’’N, 15°44’20.5’’E; parent material loess; 547 mm mean annual precipitation), was classified as a Chernozem with silt loam texture (pH ($CaCl_2$): 7.4, CEC: 208.6 mmol$_c$ kg^{-1}, C/N ratio: 11.9, carbonate: 15.8 w.-%). The soil in Kaindorf, Styria (47°13’46.0’’N, 15°50’40.6’’E; parent material tertiary sediments; 883 mm mean annual precipitation), was classified as Cambisol with clay loam texture (pH ($CaCl_2$): 6.6, CEC: 209.4 mmol$_c$ kg$^{-1,}$ C/N ratio: 13.8, carbonate: 0.0 w.-%). A detailed characterisation of the two soils was given in Kloss et al. (2013).

Experimental setup in the field

Plots had a circular shape because this geometry guaranteed the best ratio of large experimental area to low circumference. This lowered the risk of soil mixing at the outer plot zones and prevented the mixing in the inner (net) plot area. Each circular net plot (used for harvest analysis, soil and plant sampling) with a diameter of 3.5 m was positioned in the centre of a gross plot with 6.5 m diameter. The minimum distance between the outer borders of net plots was 6.5 m; the minimum distance between the outer borders of gross plots was 0.5 m. There were four different treatments with four replicates (n=4), arranged as Latin Square. Nutrients (N, P, K) were supplied according to standard agricultural practices in the respective region (Table 1). The treatments consisted of three different BC application rates (0, 24 and 72 t ha^{-1}) with identical mineral N fertilisation and one additional treatment without N supplement but with a BC application rate of 72 t ha^{-1}. The high BC application rate of 72 t ha^{-1} was chosen to simulate carbon enrichments observed in historically amended, terra-preta-like soils (Downie et al. 2011). Among the four treatments we included one BC treatment without nitrogen addition because the, for a wood-based BC, relatively high N concentration of 0.4% would have meant an N addition of 288 kg ha^{-1}. This treatment should show if at least a part of this N pool could be of any use for the crops. BC was applied to the soil by dividing each plot in 8 sub-plots; each of these received the amount of BC corresponding to the area of this sub-plot. BC was moistened by hand with a watering-can (1.5 l m^{-2}) immediately after application to avoid wind erosion. Incorporation into soil was achieved to a depth of 10 cm with a rotary hoe at low rotation speed. The experimental plots did not receive irrigation at any time, apart from the BC moistening at the initial application.

Table 1. BC application and fertilisation rates on the Cambisol and Chernozem in 2011 and 2012. N: Nitrogen; P: Phosphorus; K: Potassium. BC or fertiliser application rates are given for 2011 / 2012.

	Treatment	BC (t ha^{-1})	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
Cambisol (Kaindorf)	fertiliser without BC (control)	0 / 0	150 / 120	13 / 0	46 / 0
	24 t ha^{-1} BC + fertiliser	24 / 0	150 / 120	13 / 0	46 / 0
	72 t ha^{-1} BC + fertiliser	72 / 0	150 / 120	13 / 0	46 / 0
	72 t ha^{-1} BC without N supplement	72 / 0	0 / 0	13 / 0	46 / 0
Chernozem (Traismauer)	fertiliser without BC (control)	0 / 0	120 / 75	26 / 31	50 / 100
	24 t ha^{-1} BC + fertiliser	24 / 0	120 / 75	26 / 31	50 / 100
	72 t ha^{-1} BC + fertiliser	72 / 0	120 / 75	26 / 31	50 / 100
	72 t ha^{-1} BC without N supplement	72 / 0	0 / 0	26 / 31	50 / 100

Experimental management and sampling
Kaindorf

The addition and incorporation of BC into the Cambisol in Kaindorf took place on 31 March, 2011. The site was fertilised on 12 April, 2011 (nitrogen (N), phosphorus (P), potassium (K) = NPK; N: P_2O_5: K_2O = 20: 6: 11, Linzer Star, Borealis Linzer Agro Trade GmbH, Austria). Subsequently, maize *(Zea mays* L.) was sown on 25 April, 2011, followed by N fertilisation (Nitramoncal = 27% ammonium nitrate) on 6 July, 2011. The maize was harvested on 28 September, 2011, followed by the sowing of winter wheat (*Triticum aestivum* L.) on 10 October, 2011 and fertilised with N (Nitramoncal = 27% ammonium nitrate) on 12 March, 2012. The winter wheat was harvested on 17 July, 2012. Composite soil samples were taken on the days of harvest. From each plot we attained approximately 20 soil samples randomly from a depth of 0−17 cm and mixed.

Traismauer

Here, BC was incorporated on 16 March, 2011, followed by NPK (N: P_2O_5: K_2O = 15: 15: 15, Linzer Star) fertilisation on 11 April, 2011. Spring barley (*Hordeum vulgare* L.) was sown on 12 April, 2011 and fertilised (Nitramoncal) on 10 May, 2011. Spring barley was harvested on 21 July, 2011. Sunflower (*Helianthus annuus* L.) was sown on 20 April, 2012, and NPK (Nitramoncal = 27% ammonium nitrate and DC 45 plus (P_2O_5: K_2O = 12: 20)) added on 3 May, 2012.

Sunflower was harvested on 26 September, 2012. Composite soil samples (see above) were taken on the days of harvest.

Climate and weather conditions

In 2011, Kaindorf total annual precipitation sum was below average, with only 69.2% of the long-term mean 1971–2000 (Fig. 1). In the first nine months of 2012, the precipitation was 83.4% of the long-term mean.

Traismauer experienced a more pronounced precipitation deficit in 2011, with only 50.4% of the long-term mean 1971–2000 (Fig. 1). However, in the first nine months of 2012, precipitation was only slightly below average, reaching 93.1% of the 30-year mean.

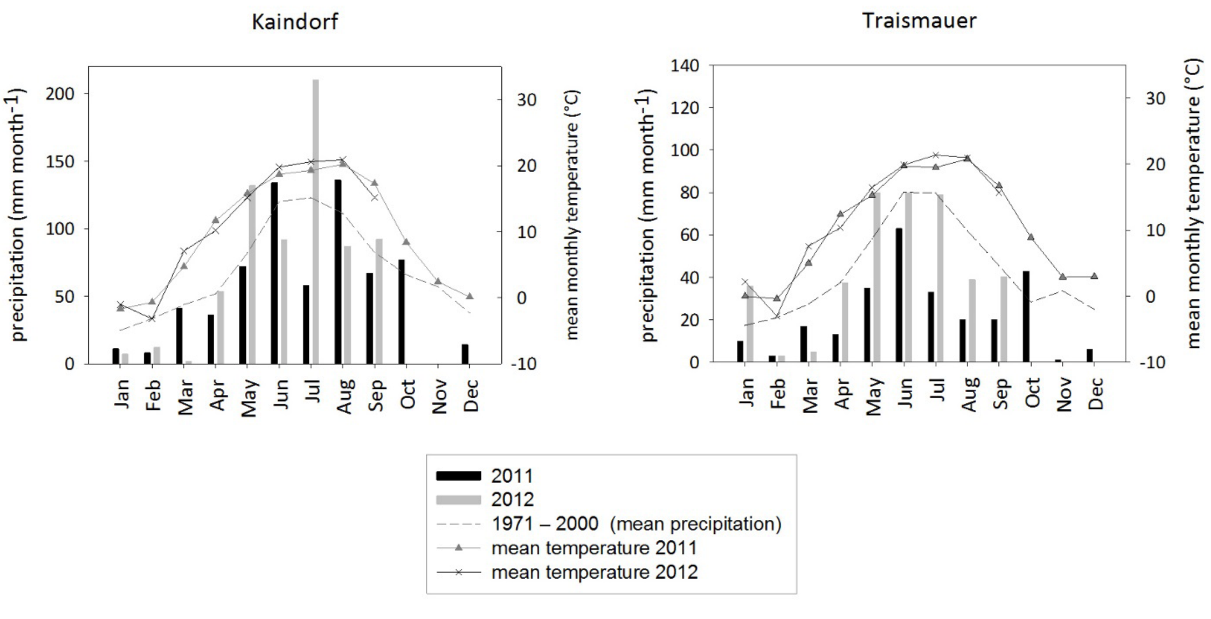

Fig. 1. Monthly precipitation and temperature at the two study sites Kaindorf and Traismauer in 2011 and 2012 compared to the mean monthly precipitation (1971–2000). Weather data for 2012 are given until September, the month of the last harvest.

Analyses of soil samples

The sampled soils were air-dried and sieved to 2 mm. The pH was measured after brief shaking with 0.01 M $CaCl_2$ solution (ratio 1:5), letting stand for 24 h and shaking again (inoLab pH Level 2P, Weilheim, Germany). The electrical conductivity (EC) was measured in a 1:10 (w:v) water extract after 24 h extraction (inoLab Cond Level 2 conductometer, Weilheim, Germany). Bulk density was determined according to the Austrian standard ÖNORM L 1051. Undisturbed soil cores were carefully taken by driving a metal cylinder with a volume of 200 cm^3 into each soil plot (n=4). The soil cores were dried at 105 °C in the laboratory and the dry weight was determined after constant weight was reached (Blake and Hartge 1986). The cation exchange capacity (CEC) was measured according to ÖNorm L 1086 (2001), extracting 5 g of soil with 100 mL 0.1 M $BaCl_2$ solution. The exchangeable cations (Ca, Mg, K, Na, Al, Fe, Mn) were measured by Atomic Absorption Spectroscopy (AAS; Perkin Elmer 2100; Überlingen, Germany); CEC was calculated as the sum of the exchangeable cations (in $mmol_c\,kg^{-1}$). Further, nitrogen supplying potential (NSP) was determined by anaerobic incubation according to ÖNorm L 1091 (1999): to this end, 15 ml of distilled water was added to 5 g of soil in each of three tubes. One tube was instantly deep-frozen to –20 °C (A); the other two tubes were incubated for 7 days at 40 °C (B). After the incubation period, the samples were shaken with 15 ml of 4 M KCl solution for 30 minutes and filtered; NH_4^+-N was determined photometrically (Agilent 8453, Waldbronn, Germany) using the Indophenol method 2 at 661 nm. The NSP was calculated as the difference between B and A. Phosphorus (P_{CAL}) and potassium (K_{CAL}) were extracted with calcium-acetate-lactate (CAL) according to ÖNorm L 1087 (2004). P_{CAL} was measured with a photometer (Agilent 8453, Waldbronn, Germany) using the molybdenum-blue method originally published by Murphy and Riley (1962); K_{CAL} was measured with AAS (Perkin Elmer 2100, Überlingen, Germany). Total carbon (C) and nitrogen (N) were determined by dry combustion, following the method of Tabatabai and Bremner (1991) and measured with an elemental analyser (CHNS-O EA 1108; Carlo Erba Instruments, Milano, Italy). Organic C (C_{org}) was calculated as the difference of total C and carbonate content, which had been determined gas-volumetrically (Burt 2004). The fertilised soil and the soil-BC mixtures were packed into metal cylinders of a size of 100 cm^3 to a desired bulk density (BD), in order to determine water holding capacity (WHC) and water retention characteristics (pF curve). WHC was only defined for soil samples (after BC application) in 2011. For determination of the WHC, the soil cores were fully saturated and placed on a moist sand bed until the excess water had drained by gravity. The soil cores were weighed after equilibrium was reached. The water retention characteristics (pF curve) of the samples were determined using the pressure chamber method (Austrian standard L 1063). The soil cores in the metal cylinders were saturated and drained at three pressure steps (6, 30 and 1500 kPa) until equilibrium was reached (Klute 1986). The water content of the samples was measured after each pressure step and after drying the samples at 105 °C at the end of the procedure. Plant available water (PAW) was calculated as the difference between pF 1.8 and 4.2, in percentage.

Analyses of plant samples

For yield analysis, the net plots (9.6 m^2 each) in the centre of each gross plot were harvested. The dried (60 °C) harvest products of maize, barley, wheat and sunflower were separated in grain and straw, chaffed and milled before analysis. Macro- and micronutrients for grain and straw of all crops were analysed with inductively coupled plasma optical emission spectroscopy (ICP-OES; PerkinElmer OPTIMA 7300DV, Waltham, MA, USA) after full acid digestion ($HNO_3 : HClO_4$ = 20 + 4 mL; based on ÖNorm L 1085, 2009). C and N were analysed with an elemental analyser (EA1108, Carlo Erba Instruments). Nutrient uptake was calculated by multiplying grain and straw dry mass of the crops with the analysed macro- and micronutrient concentrations.

Statistical analyses

All statistical analyses were conducted with STATISTICA 8. Reported results are means ± standard deviation (SD). Prior to the statistical analyses, all data were evaluated with the Dixon outlier test and outliers were eliminated before determining mean values and SD (Dixon 1950). Main effect ANOVA (analysis of variance) and Duncan's multiple range test were carried out in order to identify significant differences between the four varying treatments ($p < 0.05$). Analyses were conducted to a) identify whether BC can contribute the missing N; for that hypothesis, the 72 t ha^{-1} BC treatments with and without N application were analysed (compared by Duncan's multiple range test). The other investigation b) concentrated on the effects of different BC amounts (0, 24 and 72 t ha^{-1}) with identical mineral N supply. All four treatments were analysed in one run with a main effect ANOVA and subsequently, the means were tested with Duncan's multiple range test for significant differences.

Results

Effects on soil properties

The effects of BC application on basic soil (fertility) parameters are shown in Table 2 and Table 3. In 2011, the Cambisol (Table 2) showed significantly increased pH and EC values upon BC addition; the differences between the different treatments disappeared one year later. All BC treatments showed significantly higher C_{org} and C/N and lower BD values for both years. CEC and NSP were not significantly affected by BC application. Higher BC application rates showed significant increases of K_{CAL} in both years and of P_{CAL} in the first but not in the second year.

Unlike in the Cambisol, the pH of the Chernozem (Table 3) did not increase after BC application and even decreased significantly after the BC 72 t ha^{-1} treatment with N supplement in the first year. Concomitantly, CEC was not affected by BC application. BD was unaffected in the first year, but had significantly lower values after both BC 72 t ha^{-1} treatments in 2012, the second year of the study. Only the 72 t ha^{-1} BC treatment + N supplement induced a significant increase of EC. The 72 t ha^{-1} BC applications caused significantly higher C_{org} and C/N values in both years. In the first year, 72 t ha^{-1} BC without N supplement evoked a significantly lower NSP than with N supply, which then evened out in the second year. K_{CAL} and P_{CAL} were both significantly higher after 72 t ha^{-1} BC + N supplement in the first year.

Effects on soil water

In the Cambisol, BC application caused significant increases in WHC (Table 2). The pF curve (Fig. 2) shows that both BC 72 t ha^{-1} treatments had significantly higher volumetric water contents at pF 0. Similarly, at pF 1.8 these two treatments had the highest volumetric contents. There was no significance for the water contents at pF 2.5 while at pF 4.2 the BC 24 t ha^{-1} + N application showed the lowest volumetric water content within the BC treated soils. PAW significantly increased after 72 t ha^{-1} BC amendment, with and without N fertilisation (Fig. 2). In the Chernozem soil, BC showed similar trends in WHC characteristic than in the Cambisol but these were not statistically significant (Table 3). The pF curve (Fig. 2) showed, similar to the Cambisol, that both BC 72 t ha^{-1} treated plots had significantly higher volumetric water contents at pF 0 and pF 1.8. There was no significance in the water contents at pF 2.5 and 4.2. PAW increased through BC application, albeit not statistically significant (Fig. 2).

Effects on crop yield

If supplementary N application was absent, all crops showed significant yield decreases after 72 t ha^{-1} BC amendment (Fig. 3). In the first year of the experiment, in 2011, maize total aboveground biomass yield decreased by 37% (on the Cambisol), if N application was missing at the 72 t ha^{-1} BC treatment. In the second year, 2012, biomass yield of winter wheat decreased even more, by 71%, comparing the above-mentioned treatments. However, varying BC amendments (0, 24 and 72 t ha^{-1}) with identical mineral N supply did not cause significant differences on the total biomass yields of maize and wheat.

The individual yield analyses of grain and straw of maize and wheat showed varying results: Maize grain decreased by 45% if N application was not supplemented at the high BC application rate, while maize straw was not significantly affected. Grain and straw yield of winter wheat, however, declined to the same degree by 71% at 72 t ha-1 without N application. The varying BC applications (0, 24 and 72 t ha^{-1}) with identical N supply did not result in significant yield differences in the grain and straw yields of neither maize nor wheat.

In the Chernozem soil, the study of N deficiency after 72 t ha^{-1} BC application without N supplement revealed a lower decrease than in the Cambisol: barley (2011) and sunflower (2012) total above-ground biomass yields were reduced by 23% and 14%, respectively. For barley, the grain yield decrease was more distinct than the straw yield whereas in sunflower the decrease in straw yield was more apparent than in grain yield if N supplement was missing

At sufficient N supply, barley grain and straw as well as sunflower straw were not significantly affected after varying BC treatment (0, 24 and 72 t ha^{-1}) with identical mineral N application rates. Sunflower, however, showed slightly (+ 10%) higher grain yields after 24 t ha^{-1} BC amendment but not for total aboveground dry matter.

Table 2. Effects of BC on soil properties (n=4; mean value) of the Cambisol for 2011 and 2012. Soils were sampled immediately after crop harvest. Different letters in lines for each parameter indicate significant differences at $p<0.05$ (Duncan's multiple range test). EC: Electrical conductivity; BD: Bulk density; CEC: Cation exchange capacity; NSP: Nitrogen Supplying Potential; KCAL/ PCAL: CAL-extractable potassium/phosphorus; WHC: Water holding capacity; PAW: plant available water.

Soil parameter	BC 0 t ha^{-1}/ N 150 kg ha^{-1}		BC 24 t ha^{-1}/ N 150 kg ha^{-1}		BC 72 t ha^{-1}/ N 150 kg ha^{-1}		BC 72 t ha^{-1}/ N 0 kg ha^{-1}	
	2011	2012	2011	2012	2011	2012	2011	2012
pH	6.30^{a}	6.71^{a}	6.50^{b}	6.69^{a}	6.65^{c}	6.75^{a}	6.65^{c}	6.71^{a}
EC (µS cm^{-1})	64.3^{a}	83^{a}	67.7^{a}	97^{a}	83.3^{b}	100^{a}	89.1^{b}	94^{a}
BD (g cm^{-3})	1.26^{c}	1.36^{b}	1.15^{b}	1.26^{a}	1.09^{ab}	1.17^{a}	1.07^{a}	1.18^{a}
CEC (mmol$_c$ kg^{-1})	187^{a}	204^{a}	195^{ab}	211^{ab}	197^{ab}	209^{ab}	204^{b}	214^{b}
C/N ratio	17.6^{a}	12.74^{a}	30.5^{b}	24.35^{b}	56.0^{d}	25.07^{b}	48.8^{c}	20.84^{b}
C_{org} (%)	2.5^{a}	2.40^{a}	4.8^{b}	4.58^{bc}	8.8^{c}	5.36^{c}	7.9^{c}	3.85^{b}
NSP (µg g^{-1} d^{-1})	16.6^{a}	16.0^{a}	16.5^{a}	16.5^{a}	15.3^{a}	16.7^{a}	16.5^{a}	16.9^{a}
K_{CAL} (mg kg^{-1})	171^{a}	146^{a}	185^{ab}	188^{bc}	213^{bc}	175^{ab}	246^{c}	209^{c}
P_{CAL} (mg kg^{-1})	70.3^{a}	80^{a}	69.9^{a}	80^{a}	90^{b}	91^{a}	70.3^{a}	77^{a}
WHC (%)	47.6^{a}		51.7^{b}		57.44^{c}		57.8^{c}	
PAW (%)	16.5^{a}		18.2^{ab}		19.6^{b}		20.1^{b}	

Table 3. Effects of BC on soil properties (n=4; mean value) of the Chernozem for 2011 and 2012. Soils were sampled immediately after crop harvest. Different letters in lines for each parameter indicate significant differences at $p<0.05$ (Duncan's multiple range test). EC: Electrical conductivity; BD: Bulk density; CEC: Cation exchange capacity; NSP: Nitrogen Supplying Potential; KCAL/ PCAL: CAL-extractable potassium/phosphorus; WHC: Water holding capacity; PAW: plant available water.

Soil parameter	BC 0 t ha^{-1}/ N 150 kg ha^{-1}		BC 24 t ha^{-1}/ N 150 kg ha^{-1}		BC 72 t ha^{-1}/ N 150 kg ha^{-1}		BC 72 t ha^{-1}/ N 0 kg ha^{-1}	
	2011	2012	2011	2012	2011	2012	2011	2012
pH	7.40^{a}	7.20^{a}	7.40^{a}	7.18^{a}	7.30^{b}	7.19^{a}	7.40^{a}	7.22^{a}
EC (µS cm^{-1})	123^{a}	128.8^{ab}	128^{a}	134.1^{b}	142^{b}	140.7^{b}	122^{a}	121.6^{a}
BD (g cm^{-3})	1.29^{a}	1.44^{b}	1.30^{a}	1.35^{b}	1.19^{a}	1.16^{a}	1.21^{a}	1.16^{a}
CEC (mmol$_c$ kg^{-1})	201^{a}	198^{a}	202^{a}	210^{a}	209^{a}	209^{a}	204^{a}	208^{a}
C/N ratio	14.6^{a}	11.9^{a}	27.0^{a}	18.7^{b}	48.3^{b}	33.5^{c}	50.3^{b}	32.7^{c}
C_{org} (%)	1.72^{a}	1.87^{a}	3.28^{b}	2.97^{a}	4.91^{c}	6.54^{b}	6.56^{d}	5.89^{b}
NSP (µg g^{-1} d^{-1})	13.9^{b}	8.03^{a}	14.3^{b}	9.44^{a}	14.4^{b}	9.15^{a}	10.6^{a}	8.07^{a}
K_{CAL} (mg kg^{-1})	247^{a}	233^{ab}	277^{a}	278^{b}	396^{b}	243^{b}	265^{a}	177^{a}
P_{CAL} (mg kg^{-1})	77^{ab}	82^{c}	59^{a}	74^{bc}	94^{b}	71^{b}	55^{a}	61^{a}
WHC (%)	35.5^{a}		43.3^{a}		41.2^{a}		49.4^{a}	
PAW (%)	18.6^{a}		20.8^{a}		24.6^{a}		26.4^{a}	

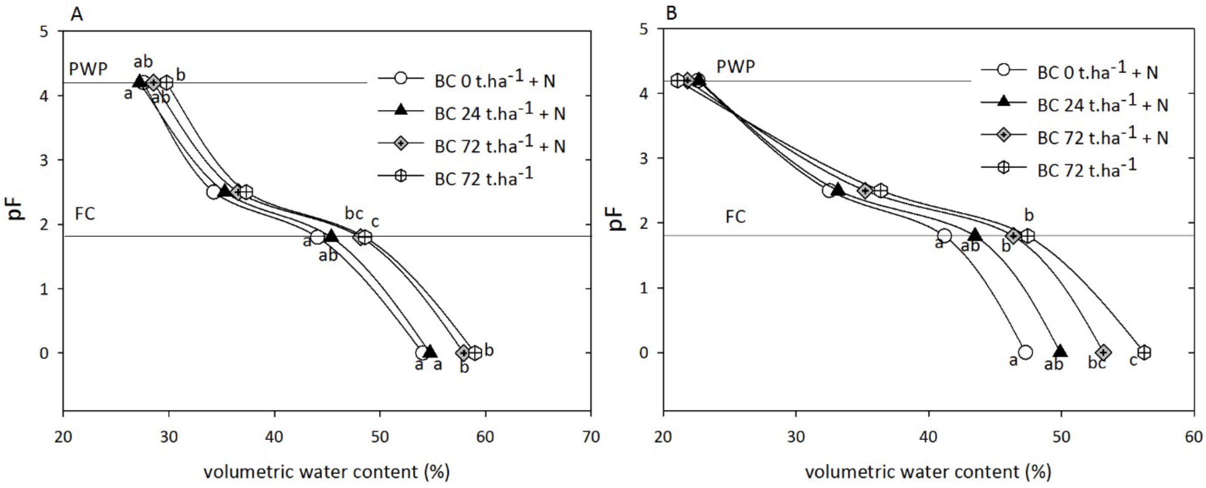

Fig. 2. pF curves of the Cambisol (A) and the Chernozem (B) (n=4). Volumetric water contents were determined at pF 0, 1.8, 2.5 and 4.2. Different letters indicate significant differences at $p<0.05$ (Duncan's multiple range test). PWP: Permanent wilting point; FC: Field capacity.

Effects on nutrient uptake

The effects of BC application on plant nutrient uptake (N, P, K, Ca, Al, B, Cu, Fe, Mn, Mo, Na, Zn) are shown in Table 4a – 4d. For the Cambisol, 72 t ha^{-1} BC without N supplement caused a significantly lower N uptake for maize (44% lower than in the treatment with the same BC rate including N supply; Table 4a). All other treatments with the same N supply but varying BC addition showed an N uptake in the range of 111−131 kg ha^{-1}. Comparable results were observed in the second crop, winter wheat, in 2012 (Table 4b). The variable BC application rates did not affect the total uptake of nearly all macro- and micronutrients analysed in this study, the same N supply provided. Only the N deficiency treatment occasionally showed uptake rates that were higher than the respective biomass yield reduction in comparison to the same BC treatment including N. This was the case for some trace elements (especially Na, Zn, Mn, Fe, Al) as well as Ca and K.

On the Chernozem soil we also observed a significant decrease of N uptake for the 72 t ha^{-1} treatment without additional N supplement for both barley (2011) and sunflower (2012) (Table 4c, 4d). This treatment also showed significantly lower uptake of P and K compared to the same BC addition but with N application. There were no significant changes in Al and Fe uptake after any BC treatment. At the same time, Mo uptake significantly decreased in both 72 t ha^{-1} BC treatments for barley (Table 4c) while it increased in the 72 t ha^{-1} BC treatment without N supplement for sunflower (Table 4d).

Table 4a. Effects of BC on nutrient uptake (grain + straw) by maize in 2011, cultivated on Cambisol. Values are means ± SD; numbers in lines followed by different letters are significantly different at $p<0.05$ (Duncan's multiple range test).

Element	BC 0 t ha^{-1}/ N 150 kg ha^{-1}			BC 24 t ha^{-1}/ N 150 kg ha^{-1}			BC 72 t ha^{-1}/ N 150 kg ha^{-1}			BC 72 t ha^{-1}/ N 0 kg ha^{-1}		
N (kg ha^{-1})	111	±	29^{b}	131	±	32^{b}	116	±	17^{b}	65	±	13^{a}
P (kg ha^{-1})	32.2	±	0.5^{a}	31.4	±	6.9^{a}	29.4	±	2.6^{a}	24.4	±	2.9^{a}
K (kg ha^{-1})	11.3	±	2.7^{ab}	15.7	±	4.2^{b}	13.3	±	2.8^{ab}	9.0	±	1.8^{a}
Ca (kg ha^{-1})	23.3	±	6.2^{a}	26.8	±	8.0^{a}	21.5	±	5.2^{a}	15.1	±	3.2^{a}
Mg (kg ha^{-1})	19.9	±	5.2^{ab}	22.8	±	5.7^{b}	19.2	±	3.0^{ab}	15.5	±	2.2^{a}
Al (kg ha^{-1})	2.65	±	1.33^{a}	3.17	±	0.61^{a}	1.83	±	0.46^{a}	3.09	±	0.69^{a}
B (g ha^{-1})	39.7	±	6.8^{a}	51.9	±	4.1^{b}	38.9	±	7.7^{a}	29.8	±	0.8^{a}
Cu (g ha^{-1})	34.1	±	13.8^{a}	39.7	±	10.5^{a}	35.1	±	9.2^{a}	19.3	±	3.7^{a}
Fe (g ha^{-1})	1778	±	1026^{a}	1968	±	400^{a}	1185	±	267^{a}	1834	±	429^{a}
Mn (g ha^{-1})	265	±	41^{b}	287	±	14^{b}	195	±	20^{a}	266	±	45^{b}
Mo (g ha^{-1})	3.34	±	1.37^{a}	3.69	±	0.22^{a}	4.02	±	0.48^{a}	3.38	±	1.00^{a}
Na (g ha^{-1})	91	±	30^{a}	112	±	26^{a}	82	±	18^{a}	96	±	11^{a}
Zn (g ha^{-1})	462	±	4^{a}	485	±	74^{a}	413	±	45^{a}	430	±	127^{a}

Table 4b. Effects of BC on nutrient uptake (grain + straw) by winter wheat in 2012, cultivated on Cambisol. Values are means ± S± SD; numbers in lines followed by different letters are significantly different at $p<0.05$ (Duncan's multiple range test).

Element	BC 0 t ha^{-1}/ N 75 kg ha^{-1}	BC 24 t ha^{-1}/ N 75 kg ha^{-1}	BC 72 t ha^{-1}/ N 75 kg ha^{-1}	BC 72 t ha^{-1}/ N 0 kg ha^{-1}
N (kg ha^{-1})	160 ± 40^{b}	159 ± 41^{b}	159 ± 25^{b}	55 ± 21^{a}
P (kg ha^{-1})	25.6 ± 5.1^{b}	27.2 ± 5.5^{b}	26.9 ± 2.5^{b}	14.7 ± 6.4^{a}
K (kg ha^{-1})	66 ± 38^{a}	92 ± 41^{a}	68 ± 5^{a}	42 ± 17^{a}
Ca (kg ha^{-1})	12.0 ± 5.5^{a}	14.8 ± 6.4^{a}	11.8 ± 2.1^{a}	12.2 ± 7.3^{a}
Mg (kg ha^{-1})	11.9 ± 2.6^{ab}	13.7 ± 3.7^{b}	12.4 ± 1.0^{ab}	7.9 ± 3.5^{a}
Al (kg ha^{-1})	0.70 ± 0.37^{a}	0.80 ± 0.57^{a}	0.48 ± 0.27^{a}	3.49 ± 2.56^{b}
B (g ha^{-1})	11.0 ± 3.0^{ab}	13.2 ± 1.2^{b}	10.9 ± 0.7^{ab}	7.5 ± 3.1^{a}
Cu (g ha^{-1})	36.7 ± 7.7^{b}	44.4 ± 1.5^{b}	37.3 ± 4.5^{b}	17.8 ± 6.9^{a}
Fe (g ha^{-1})	699 ± 226^{a}	850 ± 384^{a}	656 ± 168^{a}	1432 ± 806^{a}
Mn (g ha^{-1})	355 ± 146^{ab}	495 ± 323^{b}	360 ± 141^{ab}	256 ± 165^{a}
Mo (g ha^{-1})	5.62 ± 0.02^{a}	6.21 ± 0.53^{a}	7.93 ± 1.98^{a}	4.46 ± 2.45^{a}
Na (g ha^{-1})	72.8 ± 18.9^{a}	88.3 ± 40.2^{a}	61.4 ± 6.0^{a}	158.2 ± 104^{a}
Zn (g ha^{-1})	293 ± 62^{b}	354 ± 24^{b}	320 ± 64^{b}	162 ± 68^{a}

Table 4c. Effects of BC on nutrient uptake (grain + straw) by barley in 2011, cultivated on Chernozem. Values are means ± SD; numbers in lines followed by different letters are significantly different at $p<0.05$ (Duncan's multiple range test).

Element	BC 0 t ha^{-1}/ N 120 kg ha^{-1}	BC 24 t ha^{-1}/ N 120 kg ha^{-1}	BC 72 t ha^{-1}/ N 120 kg ha^{-1}	BC 72 t ha^{-1}/ N 0 kg ha^{-1}
N (kg ha^{-1})	155 ± 17^{b}	151 ± 20^{b}	160 ± 18^{b}	98 ± 7^{a}
P (kg ha^{-1})	20.1 ± 3.7^{bc}	18.9 ± 2.7^{ab}	21.4 ± 0.9^{c}	12.8 ± 1.6^{a}
K (kg ha^{-1})	6.6 ± 1.1^{bc}	6.2 ± 1.4^{b}	7.1 ± 0.8^{c}	4.9 ± 0.2^{a}
Ca (kg ha^{-1})	18.8 ± 0.9^{b}	15.8 ± 5.4^{ab}	16.8 ± 1.7^{ab}	12.5 ± 1.6^{a}
Mg (kg ha^{-1})	9.46 ± 0.95^{bc}	8.92 ± 1.28^{b}	9.84 ± 0.78^{c}	8.09 ± 0.10^{a}
Al (kg ha^{-1})	1.92 ± 0.78^{a}	1.57 ± 0.93^{a}	1.30 ± 0.44^{a}	0.88 ± 0.22^{a}
B (g ha^{-1})	22.8 ± 3.1^{b}	22.2 ± 3.3^{b}	25.2 ± 2.3^{c}	19.5 ± 0.4^{a}
Cu (g ha^{-1})	55.0 ± 6.9^{bc}	52.9 ± 10.0^{b}	56.9 ± 6.3^{c}	33.8 ± 10.0^{a}
Fe (g ha^{-1})	1300 ± 525^{a}	1121 ± 629^{a}	893 ± 126^{a}	580 ± 33^{a}
Mn (g ha^{-1})	205 ± 15^{b}	185 ± 43^{b}	195 ± 22^{b}	131 ± 4^{a}
Mo (g ha^{-1})	12.1 ± 2.1^{b}	9.4 ± 1.3^{ab}	8.6 ± 2.4^{a}	7.9 ± 1.1^{a}
Na (g ha^{-1})	337 ± 17^{b}	342 ± 118^{b}	370 ± 80^{b}	279 ± 22^{a}
Zn (g ha^{-1})	354 ± 29^{b}	351 ± 44^{b}	389 ± 36^{c}	265 ± 8^{a}

Table 4d. Effects of BC on nutrient uptake (grain + straw) by sunflower in 2012, cultivated on Chernozem. Values are means ± S± SD; numbers in lines followed by different letters are significantly different at *p*<0.05 (Duncan's multiple range test).

Element	BC 0 t ha^{-1}/ N 75 kg ha^{-1}	BC 24 t ha^{-1}/ N 75 kg ha^{-1}	BC 72 t ha^{-1}/ N 75 kg ha^{-1}	BC 72 t ha^{-1}/ N 0 kg ha^{-1}
N (kg ha^{-1})	140 ± 13^{b}	134 ± 13^{b}	131 ± 11^{b}	98 ± 12^{a}
P (kg ha^{-1})	20.7 ± 1.3^{b}	18.7 ± 2.4^{b}	21.1 ± 0.8^{b}	16.0 ± 2.0^{a}
K (kg ha^{-1})	127 ± 16^{c}	105 ± 14^{b}	134 ± 13^{c}	83 ± 14^{a}
Ca (kg ha^{-1})	115 ± 8^{a}	84 ± 31^{a}	124 ± 36^{a}	69 ± 16^{a}
Mg (kg ha^{-1})	29.8 ± 2.2^{b}	25.5 ± 1.4^{a}	25.0 ± 3.3^{ab}	18.9 ± 3.4^{a}
Al (kg ha^{-1})	1.17 ± 0.28^{a}	0.80 ± 0.20^{a}	1.66 ± 0.70^{a}	0.79 ± 0.49^{a}
B (g ha^{-1})	212 ± 23^{b}	172 ± 22^{ab}	212 ± 28^{b}	150 ± 24^{a}
Cu (g ha^{-1})	150 ± 15^{b}	123 ± 20^{ab}	132 ± 13^{ab}	96 ± 20^{a}
Fe (g ha^{-1})	1479 ± 1068^{a}	894 ± 491^{a}	1267 ± 536^{a}	1199 ± 1192^{a}
Mn (g ha^{-1})	192 ± 20^{ab}	154 ± 22^{ab}	200 ± 56^{b}	113 ± 22^{a}
Mo (g ha^{-1})	3.84 ± 0.62^{a}	3.22 ± 0.35^{a}	3.82 ± 0.74^{a}	5.47 ± 1.37^{b}
Na (g ha^{-1})	352 ± 59^{b}	297 ± 69^{b}	250 ± 58^{b}	139 ± 5^{a}
Zn (g ha^{-1})	337 ± 19^{a}	328 ± 43^{a}	362 ± 5^{a}	334 ± 32^{a}

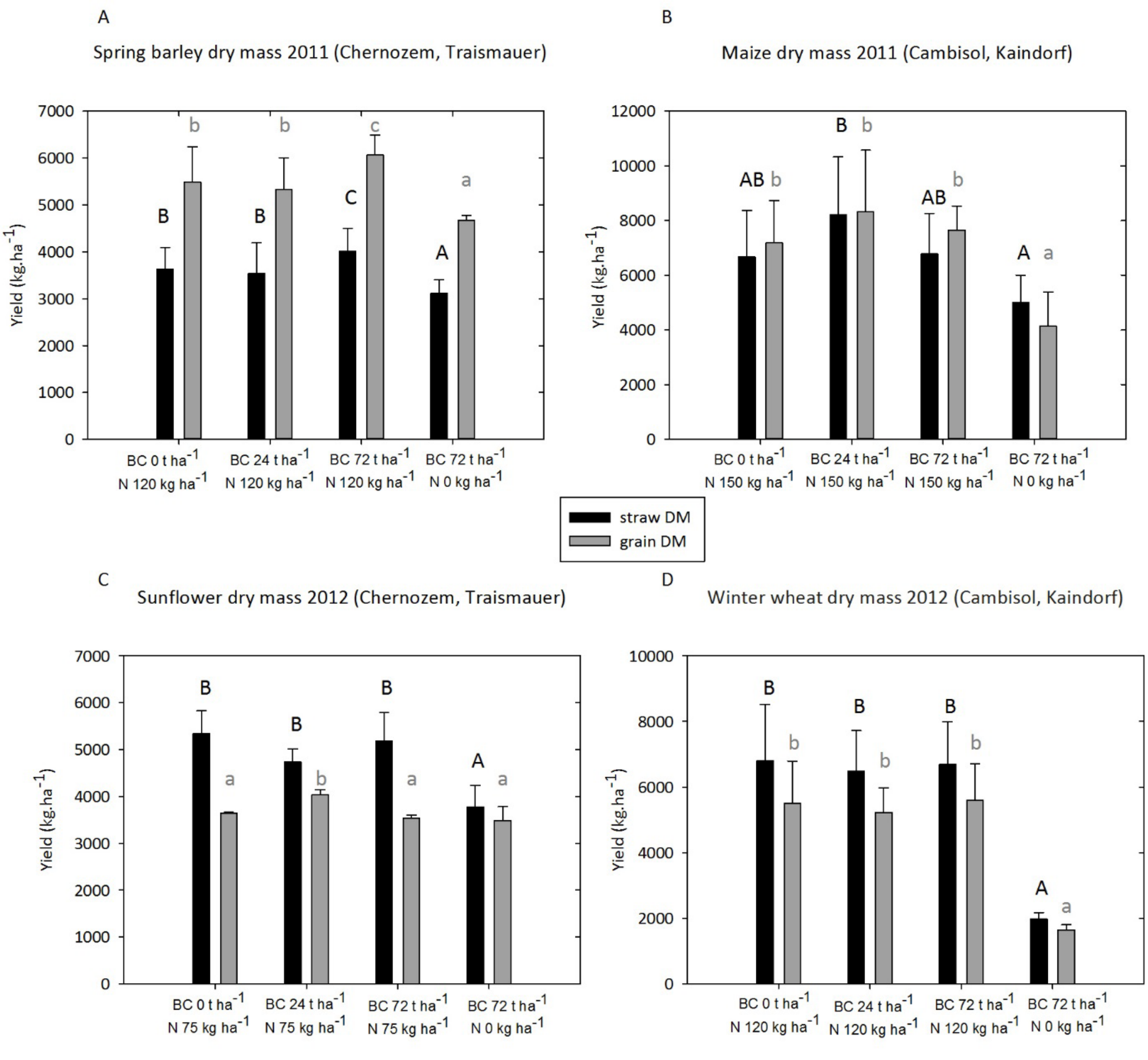

Fig. 3. Grain and straw yield (dry matter (DM) of spring barley (A), maize (B), sunflower (C) and winter wheat (D)) at varying BC and N application rates. Lower and upper case characters indicate significant differences according to Duncan's multiple range test (*p*<0.05) for grain and straw yield, respectively.

Discussion

Soil

In accordance with Karhu et al. (2011), Kammann et al. (2011) and Downie et al. (2011) our plots with BC amendment had higher WHC than plots without BC treatment. In comparison to Karhu et al. (2011), who found a WHC increase of 11% after BC amendment, the WHC of our BC-amended Cambisol was 21% higher than without BC application (see Table 2), probably because of the high application rate in our experiment. The changes in the Chernozem were in a similar range but not statistically significant. Kammann et al. (2011) found an increased drought tolerance after BC application in a greenhouse study, and Karhu et al. (2011) reported that due to the high amount of small pores in BC the soil water retention capacity was improved.

The positive effects on soil water retention in our study (pF curve; Fig. 2) were also consistent with studies from Liu et al. (2012) and Petter et al. (2012). The latter investigated the effects of eucalyptus BC in a field experiment on a course textured Dystric Plinthosol in Brazil. Liu et al. (2012) found in their field experiment that BC addition together with compost doubled the plant available WHC. Similarly, Cornelissen et al. (2013) observed increased PAW in their field experiment in West Zambia. In that study, the highest PAW was measured after using 5% maize BC in a Haplic Luvisols with silty clay. BC plots on our Chernozem were able to store approx. 10 mm more water in the upper 17 cm (depth of BC incorporation after 2 years) in comparison to plots without BC treatment. In the Cambisol, PAW was significantly higher (3.1 vol.-% increase) in the plots with the highest BC treatment (72 t ha^{-1} + N supply) than in the plots without BC application (Fig. 2). Jeffery et al. (2011) suggested in a meta-analysis that WHC was one of the reasons for crop yield increase and nutrient availability after BC application. The most positive effects in their meta-analysis were cited from a study applying 100 t ha^{-1} BC. Similarly, the highest WHC in our study was also found after the highest BC application rate, 72 t ha^{-1}. Downie et al. (2011) claimed that improved soil WHC may strengthen the case of BC as a climate change adaptation tool. Indeed, temperate climate regions, which are adversely impacted by water stress conditions, could profit from enhanced water retention effectuated by BC application.

According to Verheijen et al. (2010), most BCs cause an increase in soil pH when the initial pH in a soil is low. The positive effects of BC on plant productivity and improved crop growth may be due to a liming effect with consequences for the cycling of C and nutrients (Verheijen et al. 2010, Rajkovich et al. 2012, Powlson et al. 2011, Jeffery et al. 2011). In our study, with soils of neutral pH, a notable pH increase after BC application occurred only in the Cambisol and only in the first year, whereas the higher original pH in the Chernozem was hardly affected.

BC application generally increased CAL-extractable P and K in the first year, while these effects diminished in the second year at both sites. Fresh BCs may contain significant amounts of soluble P and K (Kloss et al. 2012), which contribute to the plant-available pool upon incorporation in the soil, but may rapidly be removed from this pool by immobilisation, plant uptake or leaching. The NSP of the studied soils was hardly affected by BC application, and thus, indicated no impairment of N mineralisation; only in the first year, the NSP was significantly lower after 72 t ha^{-1} BC treatment without additional N supplement in the Chernozem, compared to the same BC treatment but with additional N application. The impacts of BC addition on processes of the soil N cycle are frequently discussed controversially. Due to the high C/N ratio of BCs, N immobilisation in BC treated plots might be expected. An increase of soil N immobilisation after BC addition was indeed observed by Bruun et al. (2012), Zheng et al (2013b), Tammeorg et al. (2013) and Lehmann et al. (2003). However, the recalcitrant C in BC may restrict N immobilisation (Chan and Xu 2009). Bruun et al. (2012) documented in their incubation study a large influence of the BC pyrolysis method on the immobilisation of N. While BC produced with fast pyrolysis and low temperature may still contain bio-available C for the microbial population, a slow pyrolysis BC-product, as in our study, might be completely pyrolised and contain less volatile / bio-available C. Furthermore, Rajkovich et al. (2012) concluded from their greenhouse pot trial that a high pyrolysis temperature of 500–600 °C might minimise N-immobilisation. Along these lines, Novak et al. (2010) found stimulated N mineralisation after BC amendment to a forest soil in their laboratory incubation study. Clough et al. (2013) pointed at the urgency of long-term studies on N immobilisation. Most studies are short-term and N immobilisation might occur because of labile C addition in the BC. The above discussion shows that application of BC may result in varying effects on N immobilisation / mineralisation, ranging from decreased to increased mineralisation or showing no effect; the latter was observed in our study.

BC application significantly decreased bulk density in both soil types as was also observed by Abel et al. (2013) and Herath et al. (2013). Bulk density may decrease because BC itself has a much lower bulk density and higher porosity than mineral particles. Laird et al. (2010), Sohi et al. (2009), Verheijen et al. (2010) and Zhang et al. (2012)

reported positive effects of lowered bulk density (and higher organic matter content) due to BC application to the soil. These positive effects include increased nutrient cycling, retention of PAW, reduced soil compaction, increased soil aeration and increased crop yield.

Crop yield

In our study, BC treated plots (with identical N supply) showed crop yields similar to the mineral N fertilised plots. Although our experimental BC application rates were much higher than usually recommended ones, we could show that no adverse impacts on yield performance appeared, sufficient N supply provided. However, distinct yield decreases were observed, especially for maize and winter wheat on the Cambisol, when BC was applied without N supplement (Fig. 3). This emphasises the well-known effect of N availability, being the most limiting factor for crop yield. Although more N was contained in the BC additive than in the mineral fertiliser, the crops could not take advantage of this BC pool, at least not in the short term. The positive effects of improved WHC were reflected by a barley yield increase of 10% (Fig. 3A) in the first experimental year on the Chernozem site (Traismauer), where a severe precipitation deficit was recorded (Fig. 1).

Nutrient uptake

Contrary to our study, Uzoma et al. (2011) found a significant increase in nutrient uptake after BC amendment to the soil; this may have been caused by the usage of cow manure as feedstock. The authors assumed that moderate amounts of BC application (15 and 20 t ha^{-1}) may have positive effects on the soil and the resulting increased nutrient uptake may occur due to a great availability of nutrients from the soil. On the contrary, Rajkovich et al. (2012) found the highest N uptake after a low BC addition (0.2%) if BC was produced at low pyrolysis temperatures (300 °C); at addition rates of 2% or higher, the Na content of the BC reduced the growth of corn in their pot experiment. In our study, 72 t ha^{-1} BC without additional N fertiliser led to a significantly lower N uptake, mainly due to significant yield depressions. When additional N was supplied with BC, the uptake of P, K and micronutrients was not significantly enhanced by BC addition for the different crops (Table 4a – 4d). The reason for this may be the use of wood-based BC in our experiment that releases nutrients more slowly than straw-based BC (Kloss et al. 2013). However, the study of Petter et al. (2012), who also used wood-based BC (eucalyptus), showed positive effects of BC on the availability of P and Ca in a sandy soil, which may have been due to the low nutrient status of their experimental soil, the sandy texture and the relatively low soil pH of 5.6. In contrast to the increased nutrient uptake by maize that was observed by Major et al. (2010) after BC amendment on an acidic Haplustox (pH 3.9), our results of nutrient uptake from a neutral soil were less clear-cut. Alburquerque et al. (2013) found increased P, Mg and Zn uptakes and decreased K, Ca and Mg after different BC addition to a nutrient-poor, slightly acidic soil and stressed the importance of the synergistic effects of mineral fertiliser application together with BC. Similarly, P uptake in our study was slightly increased, except for maize, and K uptake was decreased, except for wheat, when BC was added with additional N compared to BC without N supplement.

Conclusions

Our results show that in temperate regions BC application may show positive effects when drought conditions impair plant growth. In a year with exceptionally low precipitation, increased WHC and PAW through BC addition might have been the reason for the observed yield increase. The decrease of soil bulk density, still observable after 2 years of field experiments, shows that application of BC can positively influence soil structure; consequently, BC can be considered as a soil amendment to increase water infiltration and to decrease the vulnerability of soils to compaction and erosion.

Nutrients from wood-based BC made a minimal contribution to the macro- and micronutrient supply of the experimental crops. Moreover, there was a negative trend in yield and nutrient uptake when N was not supplemented, indicating that even high total N pools in wood-based BC are released too slowly to contribute significantly to plant nutrition.

Our results show that the benefits of wood-based BC application to neutral, fertile soils in a temperate climate were restricted to the soil physical effects of increased WHC / PAW and lower BD. An effective provision of nutrients from BC to crops would require the use of alternative feedstocks for pyrolysis or supplementary addition of mineral or organic fertilisers. If the main objective of adding BC is carbon sequestration in soil, even at application rates as high as 72 t ha^{-1}, adverse crop growth and yield effects do not have to be suspected, sufficient nutrient supply from other sources provided.

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