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ORIGINAL PAPER

BENEFITS OF BIOCHAR AND ITS COMBINATION WITH NITROGEN FERTILIZATION FOR SOIL QUALITY AND GRAIN YIELDS OF BARLEY, WHEAT AND CORN*

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Abstract

In this 3-year-long study, significant impacts of biochar alone or in combination with nitrogen fertilization at different doses on the change in the soil chemical properties and grain yields of barley, wheat and corn were demonstrated in a field experiment established at the experimental station of the Slovak University of Agriculture in Nitra, Slovakia. Soil samples were taken from plots treated with biochar at different doses (0, 10 and 20 t ha^{-1}) and with three levels of N fertilization (0, 1^{-st}, 2^{-nd} intensity of N fertilization) during the years 2014 – 2016. The results showed that the application of biochar had a positive effect on the increase of soil pH, as the soil pH rose with the increasing application doses of biochar. The effect of biochar and its combination with N fertilizer increased SOC in the range of 8 – 79%. The mean seasonal concentrations of NO_3^- and NH_4^+ between the different treatments were not significantly different. The NH_4^+ content in the soil was affected by the application of N fertilizers, but not by biochar. The application of biochar reduced the NO_3^- concentration in the soil. The ability of biochar to increase the grain yields over the monitored period ranged from 1% up to 42%, but this effect of biochar significantly diminished two years after its application to the soil. Biochar and biochar combined with nitrogen fertilization appears to be a promising practice to improve sustainability of intensive agriculture by enhancing chemical properties of soil (increase of soil pH and soil organic matter), although the effects on grain yields are not long--term ones.

Keywords: soil organic carbon, soil pH, NO_3^- and NH_4^+ concentration, spring barley, corn, wheat.

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INTRODUCTION

Biochar can be defined as a carbon-rich product obtained by the thermal decomposition of organic material under a limited supply of oxygen and at relatively low temperatures (<700°C) (Lehmann, Joseph 2009). The term 'biochar' was first used to describe sorghum-derived activated carbon for treatment of hazardous waste. Subsequently, biochar was associated with charcoal or activated carbon obtained as a by-product when crop residues are used for bio-fuel production (Woolf et al. 2010). Indian tribes in the Amazon incorporated charred wood into soil, using this technology 2000 years ago (Mann 2002) to artificially achieve similar soil parameters as possessed by black earth even in such a warm area, where bound carbon is normally released to the atmosphere as carbon dioxide within a couple of years due to high temperature conditions. Most of biochar used has an alkaline pH and a higher content of nutrients (Van Zwieten et al. 2010), and therefore soils enriched with biochar have alkaline soil pH and are richer in phosphorus, calcium, sulphur, and nitrogen, contain more organic matter, have a high degree of microbial activity, excel in the ability to retain moisture and nutrients, and sustain their fertility for a longer time than soils without biochar applied (Mann 2002, Rajkovich et al. 2012).

The use of mineral fertilizers has played an important role in increasing agricultural productivity (Gruhn et al. 2000) in the past five decades. However, the application of mineral (nitrogen) fertilizers has been shown to contribute to a number of environmental problems including eutrophication of water bodies, drinking water pollution (Sutton, van Grisen 2011) and more rapid mineralization of organic matter (Liu et al. 2010). Therefore, it is necessary to focus on improving the soil quality, paying special attention to the soil organic matter content (SOM), as SOM positively affects soil's fertility and health. One of the possible and, at the same time, innovative solutions to the problems described above can be the application of biochar to soil. Several scientific studies have shown that biochar is a material that has the potential to mitigate climate change as a soil additive by increasing the organic carbon content in soil and improving soil's quality, thereby contributing to higher crop yields from smaller areas (Laird et al. 2010, Zhang et al. 2012). The application of organic material such as biochar and its combination with other organic or mineral fertilizers has been shown to improve the chemical (Liang et al. 2006, Horák 2015, Šimanský et al. 2018), physical (Atkinson et al. 2010, Horák et al. 2017, Igaz et al. 2018, Vitkova et al. 2017) and biological properties of soil (Lehmann et al. 2011). Other studies on biochar showed increase of crop yields, reduction of greenhouse gas emissions, and increase of carbon sequestration in the soil (Lehmann et al. 2006, Kondrlová et al. 2018). Biochar added to arable land gains some control over nitrogen (N) dynamics in the soil (Clough et al. 2013). In addition, Mierzwa-Hersztek et al. (2018) demonstrated that

NPK + poultry litter biochar at a dose of 2.25 t ha^{-1} and NPK + poultry litter biochar at a dose of 5 t ha^{-1} reduced the content of available forms of cadmium, lead and zinc. Significant increase in the activity of dehydrogenases was observed in the soil with both doses of poultry litter and biochar introduced. Co-application of NPK + poultry litter biochar at a dose of 2.25 t ha^{-1} and NPK + poultry litter biochar at a dose of 5 t ha^{-1} with mineral fertilizers also increased the total production of biomass of a pasture grass mixture compared to the NPK treatment.

Considering the importance and necessity of long-term field studies related to the impact of biochar application on arable soil, the aim of this study was to evaluate the effect of biochar application alone and in combination with mineral N fertilizers over three years of a field experiment (2014 – 2016) on changes in selected soil properties and crop yields. We aimed to resolve whether: (1) the addition of biochar improves soil properties, (2) biochar is able to counteract the increase of N inorganic forms due to additional fertilization with N fertilizers, and (3) biochar application has a positive effect on grain yields of spring barley, spring wheat and corn.

MATERIAL AND METHODS

Location of the experiment

This field-based experiment was performed at the experimental station of the Slovak University of Agriculture located in Dolná Malanta, Slovakia (48°19′00″N, 18°09′00″E). The area lies in the temperate climate zone, with the annual mean air temperature and precipitation 9.8°C and 539 mm, respectively. Table 1 shows monthly precipitation and average air temperatures during 2014 – 2016 as well as data according to 30-year climatic normal distribution (1961–1990). Prior to the field experiment, agricultural crop production at the experimental site had followed conventional management for several decades. The soil was classified as a silt loam Haplic Luvisol according to the Soil Taxonomy (IUSS WRB 2014), with the content of sand 15.2%, silt 59.9% and clay 24.9%. On average, the soil contained 9.13 g kg^{-1} of soil organic carbon, while the average soil $pH_{(KCl)}$ was 5.71.

Experimental design

The experiment was established in March 2014 and continued until 2016. Spring barley (*Hordeum vulgare* L.), corn (*Zea mays* L.) and spring wheat (*Triticum aestivum* L. var. Sensas) were sown in 2014, 2015 and 2016, respectively. The research included 9 treatments in triple replication, and was carried out on 27 plots (4 m x 6 m) arranged in a random block design. The schematic layout of the experimental design is shown in Figure 1. The spacing between the neighbouring replications was 0.5 m, and between

Table 1

Monthly precipitation and average air temperatures in 2014-2016 as well as data according to 30-year climatic normal distribution (1961-1990)

Month	(1961-1990)		2014		2015		2016	
	precipitation (mm)	temperature (°C)	precipitation (mm)	temperature (°C)	precipitation (mm)	temperature (°C)	precipitation (mm)	temperature (°C)
January	31	-1.7	34	1.0	80	-0.1	30	-2.1
February	32	0.7	35	2.9	26	-0.2	99	4.0
March	30	5.0	19	8.2	44	4.2	32	4.3
April	39	10.4	33	10.8	26	8.5	25	9.3
May	58	15.1	57	13.3	83	12.8	89	13.6
June	66	18.0	52	17.3	24	17.3	26	17.8
July	52	19.8	113	19.9	26	21.0	127	18.8
August	61	19.3	74	17.1	77	21.2	50	16.8
September	40	15.6	109	15.1	43	14.9	43	15.1
October	36	10.4	46	10.4	62	8.7	86	6.5
November	55	4.5	25	6.3	29	5.6	41	2.0
December	40	0.1	43	1.5	13	1.6	14	-2.7
Year (sum/average)	539	9.8	641	10.3	532	9.6	662	8.6

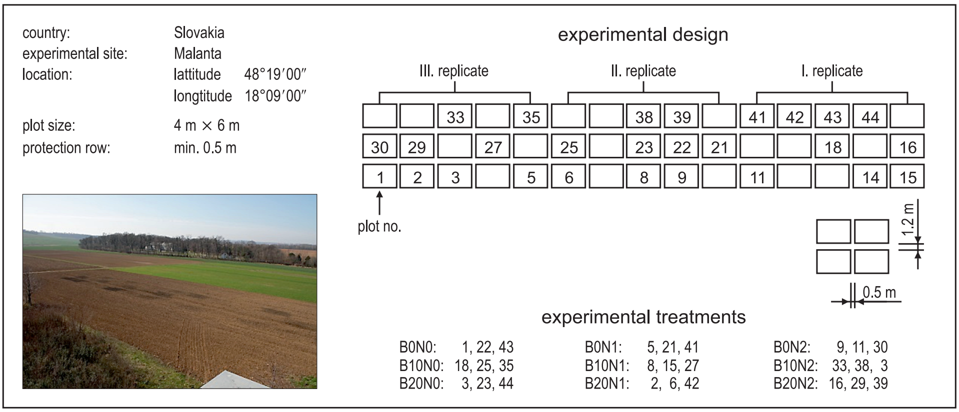

Fig. 1. Field site and schematic layout of the experimental design

rows – 1.2 m (access paths). The field was ploughed and harrowed, after which biochar was evenly applied to the soil surface and immediately incorporated into the 0 – 10 cm soil layer, combined with or without N fertilizer in spring 2014. The schedule of different agricultural management practices during the studied period is shown in Figure 2. The description and application doses for the investigated treatments are shown in Table 2.

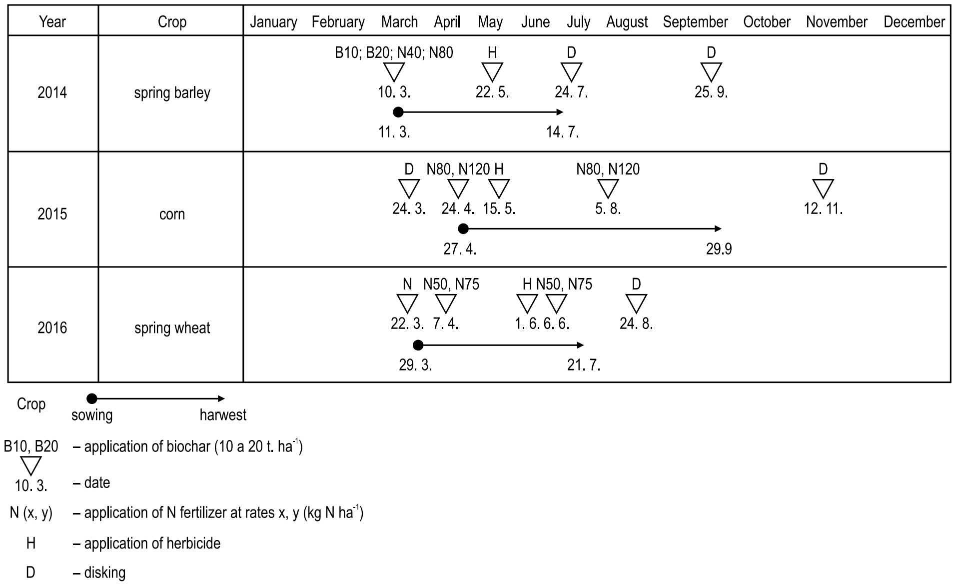

Fig. 2. Scheme of crop management practices during 2014 - 2016

Table 2

Description of the experimental treatments

Treatment	Description
B0N0	no biochar, no N fertilization
B10N0	biochar at dose of 10 t ha^{-1} in 2014
B20N0	biochar at dose of 20 t ha^{-1} in 2014
B0N1	no biochar combined with only first level of N fertilization: doses of N were 40, 160 and 100 kg N ha^{-1} in 2014, 2015 and 2016, respectively
B10N1	biochar at dose of 10 t ha^{-1} in 2014 with N fertilizer doses of 40, 160 and 100 kg N ha^{-1} in 2014, 2015 and 2016, respectively
B20N1	biochar at dose of 20 t ha^{-1} in 2014 with N fertilizer doses of 40, 160 and 100 kg N ha^{-1} in 2014, 2015 and 2016, respectively
B0N2	no biochar combined with only second level of N fertilization: doses of N were 80, 240 and 150 kg N ha^{-1} in 2014, 2015 and 2016, respectively
B10N2	biochar at dose of 10 t ha^{-1} in 2014 with N fertilizer doses of 80, 240 and 150 kg N ha^{-1} in 2014, 2015 and 2016, respectively
B20N2	biochar at dose of 20 t ha^{-1} in 2014 with N fertilizer doses of 80, 240 and 150 kg N ha^{-1} in 2014, 2015 and 2016, respectively

The biochar was produced from paper fiber sludge and grain husks (1:1 w/w). As declared by the manufacturer, the biochar was produced at a pyrolysis temp. of 550°C applied for 30 min in a Pyreg reactor. Basic chemical and physical properties of the biochar are listed in Table 3.

Table 3

Basic physical and chemical properties of applied biochar according to EBC Certificate of biochar No. 1013069001 Sonnenerde, GmbH, Austria

pH	C	N	C:N	Bulk density	Surface area	Ash
	(%)			($g\ cm^{-3}$)	($m^2\ g^{-1}$)	(%)
8.8	53.1	1.4	37.9	0.21	21.7	38.3

Soil and plant sampling and analytical analyses

The soil samples for the determination of soil pH, ammonium (NH_4^+) and nitrate (NO_3^-) nitrogen were taken in monthly intervals (March – November, 2014 – 2016), and the sampling for soil organic content (SOC) was carried out in every spring and autumn during the same period. The soil was sampled from a depth of 0 – 10 cm, and three randomly distributed soil sub-samples per plot were collected and mixed into a composite sample. Standard soil analyses were conducted for determination of soil characteristics. The content of inorganic forms of N (NH_4^+ and NO_3^-) was determined in a solution of 1% K_2SO_4 as described in Yuen, Pollard (1954). The content of NH_4^+ and NO_3^- in isolates was determined using the calorimetric method with a spectrometer (WTW SPECTROFLEX 6100, Weilheim, Germany). The soil organic carbon content (SOC) was estimated by the Tiurin wet oxidation method (Dziadowiec, Gonet 1999). Soil pH was measured potentiometrically in distilled water (1 : 2.5, soil: distilled water) using a pH meter (HI 2211, HANNA Instruments). Spring barley, corn and spring wheat were sampled at the end of the growing season on July 14, 2014, October 29, 2015 and July 20, 2016, respectively. Whole plant biomass was transported to the laboratory, where the plants were counted and roots separated from aerial biomass. Ears were separated from stems and counted. Grains were threshed in a mechanical thresher (manually in the case of corn) and counted by a digital seed counter. The grains and the remaining aerial biomass were dried separately in an oven at 60°C for at least for 5 days until completely dry, and then weighed. Final grain yield was calculated by multiplication of the total number of ears per m^2, number of grains per ear and average grain weight at 85% of dry biomass (HGCA, 2005).

Statistical analysis

The analyses were performed using the Statgraphics Centurion XV.I programme (Statpoint Technologies, Inc., USA). One-way analysis of variance (ANOVA) and the least significant difference (LSD) method were used to compare treatment means for the two levels of biochar and three levels of nitrogen application at $P \leq 0.05$.

RESULTS AND DISCUSSION

Effect of biochar and its combination with N fertilization on soil pH

On average, soil pH significantly ($P \leq 0.05$) increased in B10N0 and B20N0 treatments in comparison with B0N0 in 2014. The soil pH increased significantly in response to the doses of biochar in the following order: B0N0<B10N0<B20N0. The same trends were observed in treatments with and without added N fertilizer. In the next years (2015 – 2016), the application of biochar and its combination with N fertilization had significant effects on increase of soil pH (except B10N0 treatment compared to B0N0) (Figure 3*B*, *C*). The increase in soil pH due to application of higher doses of

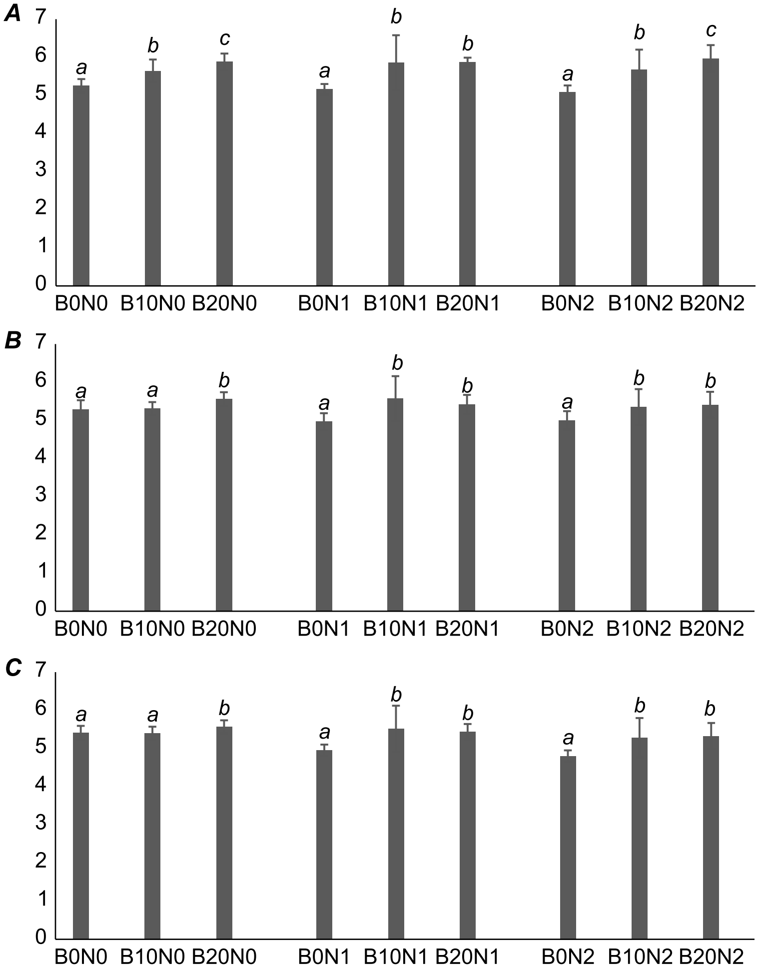

Fig. 3. Statistical evaluation of soil pH: *A* – 2014, *B* – 2015 and *C* – 2016. Different letters (*a*, *b*, *c*) between columns indicate that treatment means are significantly different at $P \leq 0.05$ according to the LSD multiple-range test

biochar was evident also in 2015 and 2016, and it was confirmed in no N fertilized treatments (B0N0<B10N0<B20N0) as well as in treatments with added biochar combined with the higher dose of N fertilizer (B0N2<B10N2<<B20N2 in 2015 and in 2016). Our results are consistent with the findings from the study by Yuan et al. (2011b), who reported an increase in soil pH value after the application of biochar with higher pH than the pH of the control. Also, other studies showed a distinct increase of soil pH with the increasing biochar application dose (Yuan et al. 2011*a*, Atkinson et al. 2010, Zhang et al. 2012, Jones et al. 2012, Horák 2015). The increase in soil pH following organic material amendment was mainly due to the presence of organic anions in added materials, as indicated by the concentration of excess cations over inorganic anions, also termed as ash alkalinity (Yan et al. 1996).

Effect of biochar and its combination with N fertilization on NO_3^- and NH_4^+ concentration

Neither form of inorganic N (NO_3^- and NH_4^+) showed a statistically significant difference of their concentration in the soil between the treatments throughout the studied period. In general, the mean NH_4^+ concentration was higher in fertilized treatments in comparison with the unfertilized control as a result of N fertilization during 2014 - 2016. In 2014, soil concentration of NH_4^+ was affected by N fertilization but not by biochar (Figure 4*A*), which confirms the findings of Apple, Klein (2015) that biochar had no significant effect on soil NH_4^+ content. However, the results showed slightly higher concentrations of NH_4^+ in both unfertilized biochar treatments in 2014 compared to the controls. However, lower NH_4^+ concentrations were observed in biochar treatments combined with N fertilizers as well as without fertilization in 2015 (Figure 4*B*). The same trend was observed in 2016 (Figure 4*C*), when the application of biochar in combination with fertilization as well as without N-fertilizers decreased NH_4^+ concentrations. These results are consistent with other studies (Le Leuch, Bandosz 2007, Taghizadeh-Toosi et al. 2011), where decreased NH_4^+ concentrations were observed, causing a reduced ammonia volatilization potential (NH_3). The study of Jones et al. (2012) documents the biochar capacity to absorb NH_4^+ and thereby reduce the availability of NH_4^+ for autotrophic conversion to NO_3^- (Lehmann et al. 2011, Spokas et al. 2012). Enhanced sorption of NH_4^+ could at least temporarily produce localized concentrations for microbial use or intake of these nutrients by crops. Increased NH_4^+ sorption also reduces the risk of nitrogen losses by leaching and maintains higher nitrogen concentrations in the surface layer of soil (Steiner et al. 2007).

In the case of nitrate (NO_3^-), lower NO_3^- concentrations were observed in 2014 in all biochar treatments as compared to their respective controls (Figure 4*A*). Our data are consistent with the research results that indicated a decrease in the NO_3^- concentration after biochar application into soil

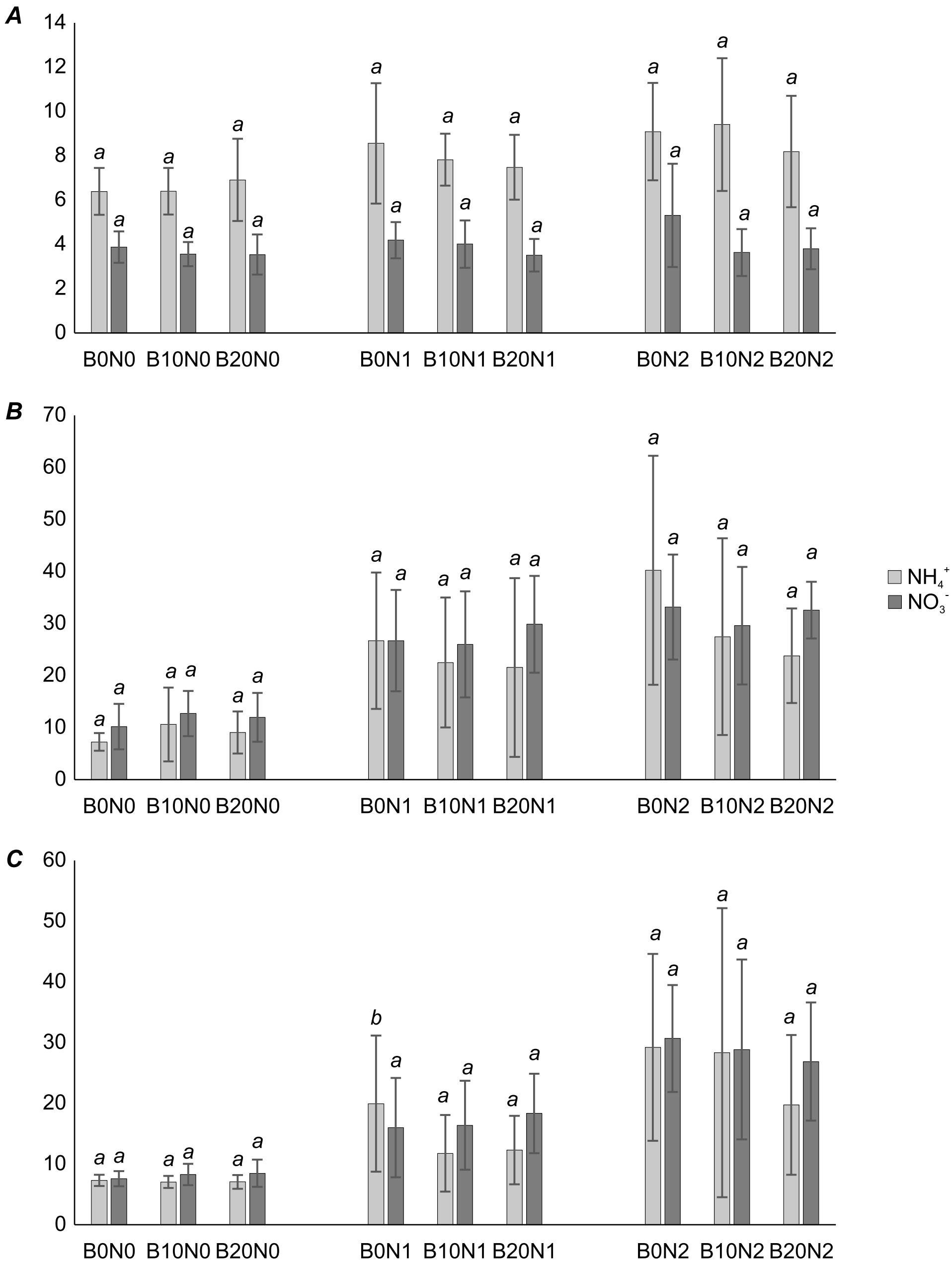

Fig. 4. Statistical evaluation of N-NH_4+ and N-NO_3-: *A* – 2014, *B* – 2015 and *C* – 2016. Different letters (*a*, *b*) between columns at the same colour indicate that treatment means are significantly different at $P \leq 0.05$ according to the LSD multiple-range test

(Ippolito et al. 2012, van Zwieten et al. 2010, Horák et al. 2017). The lower availability of NO_3^- is attributed to microbial immobilization after biochar application (Ippolito et al. 2012, Singh et al. 2010). In our case, however, these lower NO_3^- concentrations were statistically insignificant, as were the results of the statistically insignificant NO_3^- biosynthesis produced from wood biomass described by Jones et al. (2012). In 2015, lower NO_3^- concentrations were observed in biochar treatments in combination with N fertilizers (B20N1, B10N2 and B20N2) as compared to their controls (B0N1 and B0N2) and to the higher concentrations of NO_3^- in biochar treatments without application of N fertilizers (Figure 4*B*). Lower NO_3^- concentrations were observed in 2016 in the biochar treatment in combination with a higher N-fertilizer dose (150 kg N ha^{-1}) – Figure 4*C*. A reverse trend was observed for biochar application in combination with a lower dose of N fertilizer (100 kg N ha^{-1}), where the NO_3^- concentration increased in comparison with the control treatments (B0N0 and B0N1). The results of our research on the concentrations of the two forms of mineral nitrogen (NH_4^+, NO_3^-) are consistent with the study by Ducey et al. (2013), where the reduction of nitrogen mineralization was determined (conversion from organic N to the mineral forms NH_4^+, NO_3^-, which subsequently can be taken by crops). At the same time, the elapsed time after biochar application to the soil affects the potential of N mineralization, hence the ambiguity of our results in 2015 and 2016.

Effect of biochar and its combination with N fertilization on SOC

In general, application of biochar and its combination with N fertilizers or without fertilization increased the SOC content during the years 2014 - 2016 as compared to the control (Figure 5). In the first year (2014), the SOC content at the beginning and end of the growing season (GS) was higher in treatments with biochar. The treatments that included biochar in combination with N fertilization significantly ($P \leq 0.05$) increased the SOC in spring sampling. At the end of the GS, the SOC content was statistically significantly higher only in the B20N1 treatment compared to B0N1. At the end of GS in the first year (2014), the SOC in B10N0, B20N0, B10N1, B20N1, B10N2 and B20N2 was higher by 8 – 79% compared to the relevant controls (B0N0, B0N1 and B0N2). In the second and third year of the experiment (2015 and 2016), the SOC content at the beginning and at the end of the GS was also generally higher (insignificantly) in treatments with biochar compared with the control (Figure 5*B*, *C*). The exceptions were observed in autumn sampling for B10N0 in 2015, for B10N2 and B20N2 in 2016, and in spring sampling for B20N1 in 2016, where higher values of SOC were measured at their controls (B0N0 in 2015 and B0N2 in 2016). At the end of GS in 2015, the SOC in treatments B10N0, B20N0, B10N1, B20N1, B10N2 and B20N2 was higher by 16 up to 82% in comparison to control treatments (B0N0, B0N1 and B0N2) – Figure 5*B*. The same trend was observed at the end of GS in 2016, when the SOC in B10N0, B20N0, B10N1,

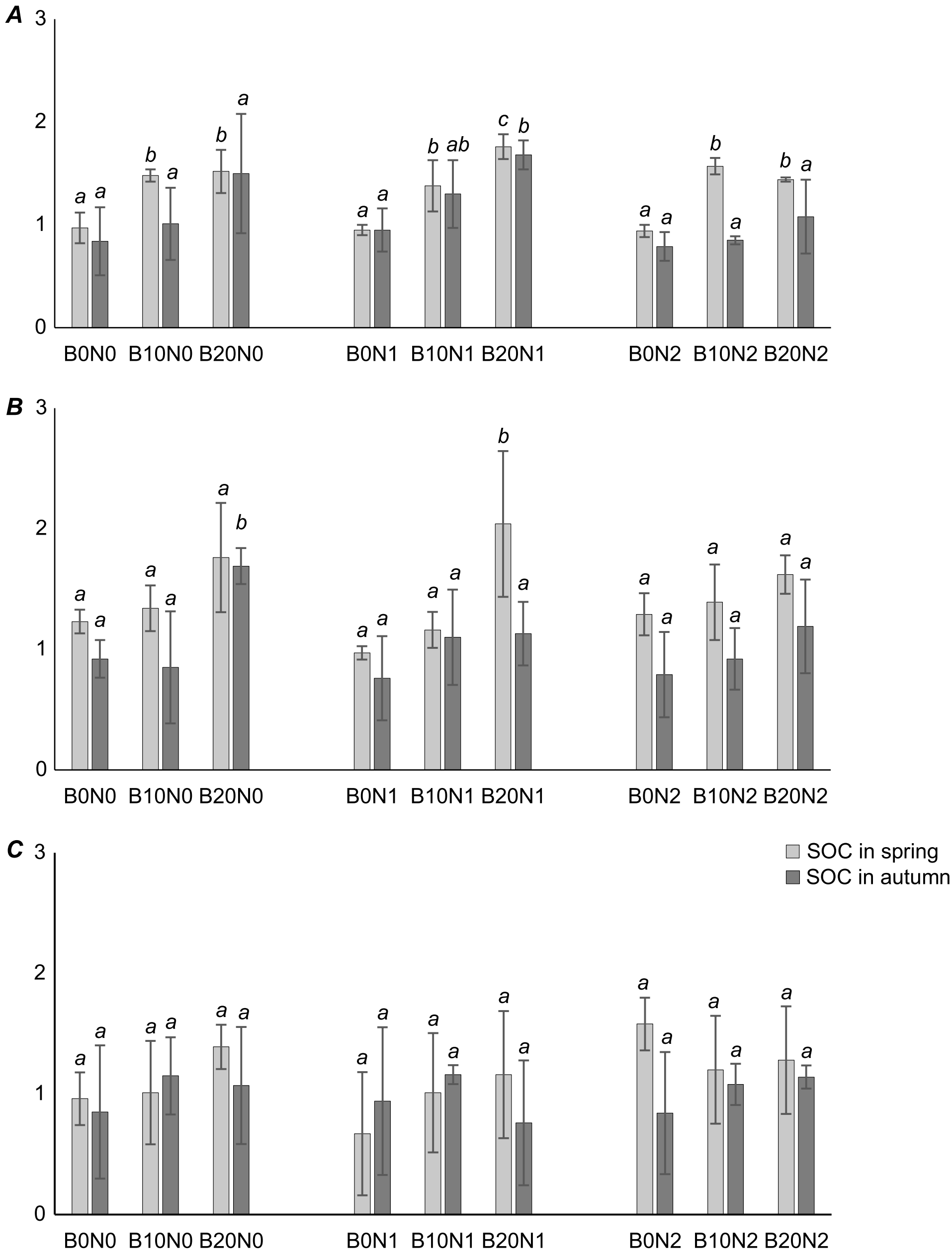

Fig. 5. Statistical evaluation of SOC: A – 2014, B – 2015 and C – 2016.
Different letters (a, b) between columns at the same colour indicate that treatment means are significantly (c) different at $P \leq 0.05$ according to the LSD multiple-range test

B20N1, B10N2 and B20N2 was higher (although not significantly) by 23 up to 36% in comparison to B0N0, B0N1 and B0N2 treatments. Biochar is considered as a soil amendment which contributes to an increase of carbon sequestration (Singh, Cowie 2014, Han et al. 2016, Šimanský et al. 2016, Šimanský et al. 2018), because the decomposition of the original organic carbon in the soil is often less intensive after biochar application (Jones et al., 2012, Cross, Sohi 2011, Keith et al. 2011). These findings are consistent with our study because the soil analysis showed that the SOC content was generally higher in treatments where biochar was applied compared to the control treatments (Figure 5). This effect of biochar can also be caused by increasing the resistance of soil organic matter to microbial degradation that may be related to the "priming effect", as reported by Fisher, Glaser (2012), which consists of short-term changes in the soil organic matter balance.

Effect of biochar and its combination with N fertilization on crop yields

The ability of biochar to increase crop yields was observed only in the first two years of the experiment (2014 and 2015), and this effect was almost eliminated in the last year (2016). In most cases, differences in grain yields were statistically insignificant (Table 4). In 2014, only fertilized and unfer-

Table 4

Effect of biochar and N fertilizer application on crop yield parameters (mean ± standard error, n = 3)

Treatments	Spring barley (2014)		Corn (2015)		Spring wheat (2016)	
	grain yield (t ha^{-1})	comparison to control (%)	grain yield (t ha^{-1})	comparison to control (%)	grain yield (t ha^{-1})	comparison to control (%)
No fertilizer: level N0						
B0N0	3.6±0.8*a**		13.6±1.5*a*		3.5±0.7*a*	
B10N0	5.1±0.9*b*	+42	13.9± 0.9*a*	+2	3.1±0.3*a*	-11
B20N0	3.2±0.5*a*	-11	12.7±2.8*a*	-7	3.3±0.04*a*	-6
Fertilized (treatments): level N1						
B0N1	3.7±0.5*a*		8.6±1.4*a*		4.2±0.6*a*	
B10N1	3.9±0.2*a*	+5	8.7±1.7*a*	+1	3.8±0.5*a*	-10
B20N1	3.6±0.5*a*	-2	9.0±0.6*a*	+5	4.1±0.4*a*	-2
Fertilized (treatments): level N2						
B0N2	5.0±0.3*a*		8.6±0.3*a*		4.5±0.9*a*	
B10N2	5.4±0.9*a*	+8	9.9±2.5*a*	+15	4.5±0.8*a*	0
B20N2	4.9±0.4*a*	-2	10.6±0.9*a*	+23	5.3±0.3*a*	+18

* Different letters in the same column represent significant differences between treatments at the $P < 0.05$ corresponding to the LSD test. Negative value represents a decrease in the final grain yield after biochar application in comparison to the relevant control without biochar.

tilized treatment with biochar at a dose of 10 t ha^{-1} increased grain yield of spring barley in a range from 5 up to 42%, and significant differences were determined between the B10N0 and B0N0 treatments. Lower grain yield of spring barley (in the range of 2 – 11%) was observed in comparison to the control in treatments with the higher biochar dose (20 t ha^{-1}). These results from the first year of the experiment are consistent with findings from other studies on the effect of biochar application on spring barley (Nelissen et al. 2015, Karer et al. 2013, Horák et al. 2017). In 2015, grain yields for all biochar treatments were higher by 1% up to 23% compared to their control treatments (no biochar), with the exception of the B20N0 treatment, where grain yield decreased by 7% compared to the B0N0. However, these results were not statistically significant. In the last year (2016), a decline in the grain yield of wheat (from 2 up to 10%) was observed in all treatments with biochar. An exception was detected for the B20N2 treatment, where grain yield increased by 18%, and the B10N2 treatment, which resulted in the same yield as control (B0N2).

CONCLUSIONS

The results of our study suggest that biochar application had a positive effect on soil pH, with soil pH increasing in response to the increasing application dose of biochar. The application of biochar to soil can generate a significant agronomic benefit associated with a possible amelioration of acidity of agricultural soils (liming effect) because the pH affects the availability and intake of nutrients. Our results point to an increase in the SOC, ranging from 8 to 79%, in soils enriched with biochar. This effect of biochar appears to be due to the increased resistance of soil organic matter to microbial degradation (the so-called negative priming effect). The mean seasonal concentration of NO_3^- and NH_4^+ between the different treatments was not significantly different. In general, it was found that the mean NH_4^+ concentration was higher in fertilized treatments as compared to their unfertilized controls. The NH_4^+ content in the soil was affected by the application of N fertilizers, but not by the application of biochar. Furthermore, a decrease in the NO_3^- concentration was observed after the addition of biochar to the soil, which was attributed to the microbial immobilization after the soil application of biochar. Our triennial results of crop yields showed the biochar potential to increase crop yields by 1% up to 42%, but this effect nearly disappeared after two years of biochar application to the soil.

Based on our results obtained on Haplic Luvisol fields, we recommend the application of lower doses biochar without N-fertilizer application to increase crop yields. However, in the subsequent years we recommend to apply higher doses of N-fertilizer to the soil where biochar had been previously added. To be able to recommend responsibly a dose of biochar as well as

N-fertilization or their combinations in agricultural practice, further research on several soil types with different crops is needed. Biochar and biochar combined with nitrogen fertilization appears to be a promising practice to improve sustainability of intensive agriculture by enhancing chemical properties of soil (increase of soil pH and soil organic matter), although the effects on grain yields are not long-term ones.

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