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Effect of biochar on N_2O emission, crop yield and properties of *Stagnic Luvisol* in a field experiment

Elena Y. RIZHIYA[1], Irina M. MUKHINA[1], Eugene V. BALASHOV[1], Vladimír ŠIMANSKY[2], Natalya P. BUCHKINA[1]

[1]Agrophysical Research Institute
Grazhdansky 14, 195220 St. Petersburg, Russia
E-mail: buchkina_natalya@mail.ru

[2]Slovak University of Agriculture, Faculty of Agrobiology and Food Resources
Tr. A. Hlinku 2, 949 76 Nitra, Slovakia

Abstract

Soils are one of the main sources of nitrous oxide (N_2O) in agriculture. Soil management practices can significantly affect N_2O emissions through changing soil physical, chemical and biochemical properties. Application of biochar to arable soils can be an option for N_2O emission mitigation, but the effect of biochar can be different for soils with different fertility levels. The objective of this study was to evaluate the effect of biochar application on N_2O emission, soil properties and barley yield from loamy sand *Stagnic Luvisol* with high and medium levels of fertility caused by high rates of farmyard manure and fertilizer application for 10 years. A small-scale field experiment was conducted during the growing season of 2012 in North-Western Russia. Four treatments were used in the experiment: 1) control (no biochar, no N-fertilizer), 2) biochar (12 t ha^{-1}), 3) N-fertilizer (90 kg ha^{-1} N) and 4) biochar (12 t ha^{-1}) + N-fertilizer (90 kg ha^{-1} N), in five replicates. Significant changes in water-holding capacity and the amount of available nitrogen (N) occurred in the soil with high fertility, and thus it emitted significantly more N_2O for the growing season than the soil with medium fertility. Biochar application effect on N_2O emissions depended on the soil management history and was reducing the emission from the soil with high fertility rich in mineral N and C but not from the soil with medium fertility if no nitrogen fertilizer was applied to the latter soil. The yield-scaled N_2O emission was the highest from the control treatments for the soil with both fertility levels, and the soil with high fertility was always characterized by higher yield-scaled N_2O emissions than the soil with medium fertility. Application of biochar reduced yield-scaled N_2O emission from the soil with medium and high fertility levels showing that biochar application to the soil can improve N use by the plants.

Key words: biochar, N_2O emissions, small-scale experiment, soil fertility, soil properties, yield-scaled emissions.

Introduction

It is well known that a regular application of farmyard or green manure to a light-textured soil contributes to higher soil fertility due to decreasing soil bulk density, increasing mineral nitrogen (N) and organic carbon (C) content, increasing soil porosity and water-holding capacity (Dabek-Szreniawska, Balashov, 2007; Ding et al., 2007; Buchkina et al., 2013). Apart from this positive effect, application of manures can cause increased nitrous oxide (N_2O) fluxes (Broucek, 2017), supported by higher content of total organic C and plant-available N.

One of the tools for an essential improvement of soil fertility and quality could be biochar application (Glaser et al., 2002; Horak et al., 2017). Biochar is manufactured through the pyrolysis of biomass feedstocks at temperatures of 300–800°C under complete exclusion of oxygen (Lehmann et al., 2003; Yanai et al., 2007; Van Zwieten et al., 2010 b). Biochar is a heterogenenous material which, due to its aromatic structure, is highly recalcitrant in soils with long-term residence time. Incorporation of biochar into arable soils can result in an improvement of their physical (porosity, aeration) and physico-chemical (pH, cation exchange capacity) properties, because porous, carbonaceous biochar with a high affinity to adsorption of water, cations (Ca, Zn and Mn) and organic substances demonstrates a high water-holding and cation exchange capacity (Saarnio et al., 2013; Tesfahun, 2018).

In some experiments, a decrease in N_2O emission from agricultural soils was often observed after application of biochar of different origin due to a lower mineral N availability and higher mineral N

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immobilization, while in other experiments the results were opposite (Sun et al., 2017). Several mechanisms such as increasing soil pH values, enhanced soil air exchange and electro-chemical properties of biochars have been suggested, which may result in reduced N_2O emissions in the presence of biochar (Ameloot et al., 2016).

The addition of biochar into soils with different N availability can result in an immobilization of soil mineral N (Lehmann et al., 2003) and as a result soil N availability for plants can be insufficient to provide optimum conditions for their growth. Nguyen et al. (2017) conducted a meta-analysis using 56 studies with 1080 experimental cases and found that biochar was reducing soil inorganic N content regardless of the experimental conditions.

Based on the results of the different experiments conducted so far, it is possible to conclude that biochar can have different effects on N_2O emissions, soil properties and crop yields from soils with different management history. The objective of the present study was to evaluate the effect of biochar application on N_2O emission, soil properties and barley yield from soils with different fertility levels resulting from the well-documented differences in soil management for 10 years. The hypothesis was that biochar amendment will affect the abovementioned parameters and that the effect will depend on the soil fertility.

Materials and methods

A small-scale field experiment was conducted during the growing season of 2012 at two plots of a big field experiment which was established in 2003 at the Experimental Station (59°34′ N, 30°08′ E) of the Agrophysical Research Institute in the St. Petersburg region of Russia, with the main goal to improve soil fertility and to find out the way of sustainable soil management. The studied soil was loamy sand *Stagnic Luvisol* (WRB, 2014), and the two plots where the small-scale field experiment was established had soil of the same type but with medium and high fertility levels. The differences in the soil properties resulted from different soil management practices since 2003 are given in Table 1. The soil with medium fertility was not receiving any manure, while the soil with high fertility received 700 t ha^{-1} of farmyard manure in 10 years. More detailed information on the applied soil management practices of the field experiment is presented in the papers of Buchkina et al. (2010; 2012).

Table 1. Properties of loamy sand *Stagnic Luvisol* with medium and high fertility

Soil fertility	Soil acidity (pH_{KCl})	Soil organic carbon g kg^{-1} C soil	Total nitrogen g kg^{-1} N soil	Mineral nitrogen mg kg^{-1} N soil	Bulk density g cm^{-3}
Medium	5.6	18.0	1.6	10.5	1.4
High	6.5	23.0	1.9	47.7	1.2

The small-scale field experiment was conducted in forty bottomless plastic buckets (22 litres in volume and 30 cm in diameter) which were placed at an area of 5 m^2 and dug into the topsoil, twenty at each plot. Four treatments were used in the experiment: 1) control (no biochar, no N-fertilizer), 2) biochar (12 t ha^{-1}), 3) N-fertilizer (90 kg ha^{-1} N) and 4) biochar (12 t ha^{-1}) + N-fertilizer (90 kg ha^{-1} N). There were five randomized replicates of each treatment at each plot. The mineral N-fertilizer used in the experiment was ammonium nitrate (NH_4NO_3). The fertilizer and the biochar were mixed with the topsoil at the beginning of the experiment. Spring barley (*Hordeum vulgare* L.) was grown in the experiment.

Biochar was produced at a char factory in St. Petersburg region of Russia from small birch logs and branches using a large temperature controlled kiln (Юдкевич, 2010). The temperature of the pyrolysis was 650°C and oxygen level was maintained at 15%. According to Bruun et al. (2012), the product is a slow pyrolysis biochar. Before incorporation into the soil biochar was manually ground and passed through a 5-mm mesh sieve. Some properties of the biochar are given in Table 2.

Table 2. Chemical and physical characteristics of biochar

Total carbon g kg^{-1}	Total nitrogen g kg^{-1}	C:N	Soil acidity (pH_{H2O})	Moisture content %	Ash content %
825.5	5.73	144.1	7.0	1.92	0.23

To calculate direct nitrous oxide (N_2O) emissions from the soil, gas samples were collected once a week (between noon and 2 pm) from 29th of May to 30th of August using closed chamber technique (Buchkina et al., 2010). The chambers were made of inverted cylindrical plastic buckets of 18.9 cm in diameter and 27 cm high. Every time before gas sampling chambers were pressed into the topsoil to a depth of 2 cm. A three-way tap on the top of each chamber was closed only after the chamber was fixed into the topsoil to avoid extra air pressure inside the chamber. After 60 min gas samples were collected via the three-way taps with a 60-ml syringe. Afterwards 50 ml of gas sample was flushed through a 10-ml glass vial that had been previously flushed with air, and then the remaining 10 ml of gas sample was forced into the vial to over-pressurize it. The same technique of gas sampling was used in our earlier N_2O field experiments (Buchkina et al., 2010; 2012; 2013). Three-ml gas subsamples from the vials were analysed for N_2O concentration with a gas chromatograph Carlo Erba 4130 (Italy) fitted with an electron capture detector. The gas chromatograph was calibrated with standard gas mixtures. The detection limit for the sampling / analytical system was 0.05 ppm. Cumulative N_2O fluxes were calculated by plotting daily N_2O emissions through time, interpolating linearly between them, and integrating the areas under the curves (Dobbie, Smith, 2003; Buchkina et al., 2010). The topsoil (5–15 cm) moisture content was measured weekly by gravimetric method and mineral N content ($N\text{-}NO_3^-$ and $N\text{-}NH_4^+$) was measured with ion-selective electrodes (Растворова, 1983; Soil survey…, 2004). Grain yield of spring barley was recorded at the end of the experiment.

Weather conditions. Weather parameters (daily mean air temperatures and precipitation) were received from the Menkovo Weather Station, situated in about 200 m from the experimental site. Mean daily air temperature during the period of measurements in 2012 ranged from +8.9 to +26.3°C with an average of +14.4°C in June, +18.5°C in July and +15°C in August. There were 401 mm of precipitation for three months (with an average for 1985–2012 being 355 mm). Out of the 94 days of the experiment there were 35 days with rainfall. The amount of rainfall was higher than 30 mm on 4 occasions, between 10 and 30 mm on 5 occasions, between 5 and 10 mm on 10 occasions and less than 5 mm on 18 occasions. July, the hottest month of the three, was also the driest with only 43.4 mm of rainfall, while there were 142.3 mm of rain in June and 215.3 mm in August. There were two periods without precipitation: 8 days in early June and 10 days at the beginning of July (Fig. 1).

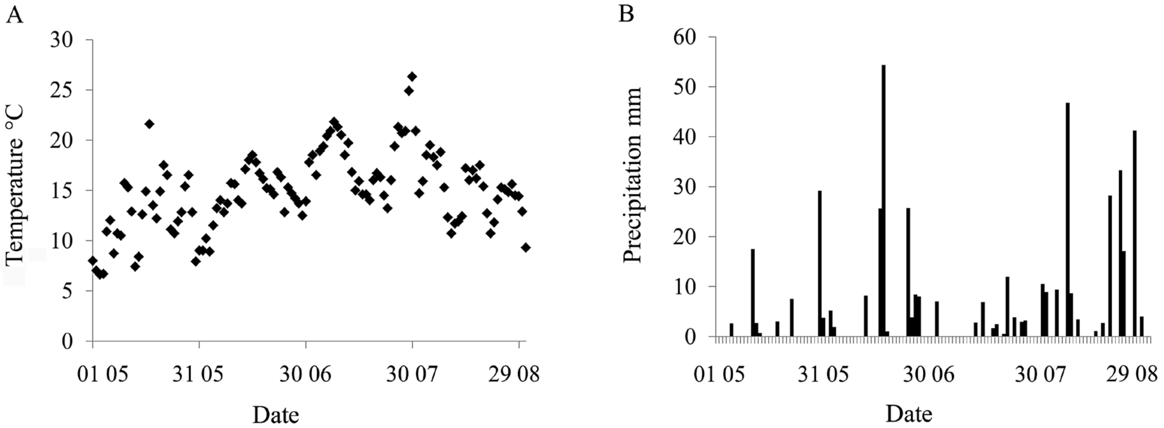


Figure 1. Mean daily air temperature (A) and daily precipitation (B) in the studied area during the wheat growing season of 2012

Means and standard deviations were calculated for each parameter in each treatment. Significance of differences between the treatments was estimated by analysis of variance (one-way *ANOVA*) at $P \leq 0.05$. The post-hoc Tukey's HSD (honestly significant difference) test was performed to find significant differences between the experimental treatments.

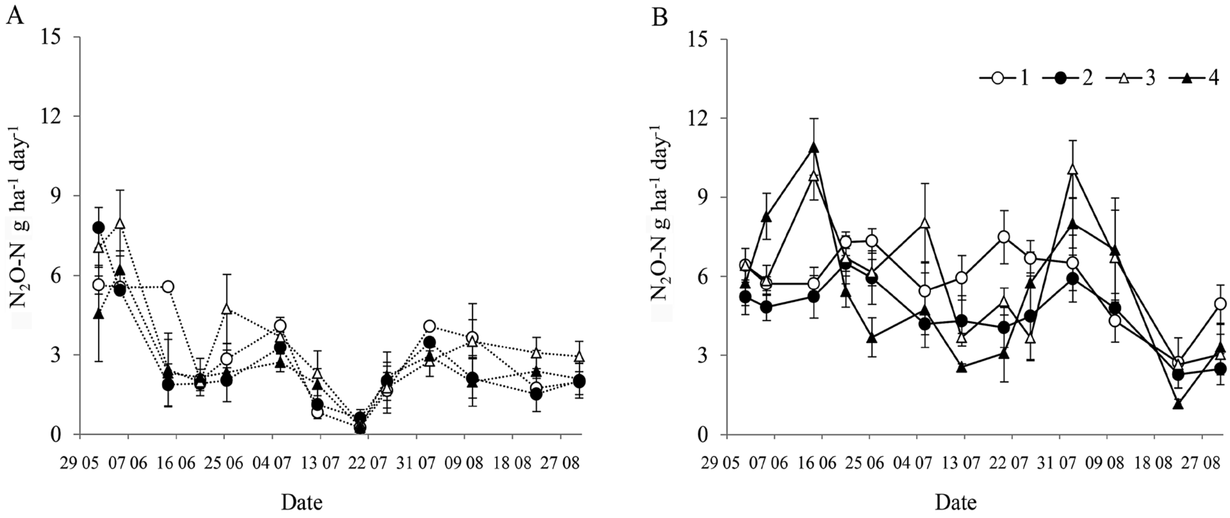
Results

Daily and cumulative nitrous oxide (N_2O) fluxes. Daily N_2O emissions from the soil with medium fertility for all the different treatments varied between 0.25 and 7.8 g $N\text{-}N_2O$ ha^{-1} day^{-1} and were at their maximum values at the beginning of the experiment and then decreased to smaller values with the minimum measured during the period following the dry spell in the weather in July. For the soil with high fertility daily N_2O fluxes varied between 1.17 and 10.91 g ha^{-1} $N\text{-}N_2O$ day^{-1} and were significantly higher ($P < 0.001$) than those from the soil with medium fertility for all the studied treatments. The lowest fluxes from the soil with high fertility were also observed after the dry spell in July, but the highest fluxes were measured not only at the beginning of June, when the N-fertilizer and biochar were applied to the soil, but also at the beginning of August. Daily N_2O fluxes from the soil with medium fertility less often exceeded 5 g ha^{-1} $N\text{-}N_2O$ day^{-1} than those from the soil with high fertility (15–20% and 40–80% for all the different treatments, respectively). There were only 4 daily fluxes from the soil with medium fertility exceeding 6 g ha^{-1} $N\text{-}N_2O$ day^{-1}, while for the soil with high fertility level there were 18 such occasions for all the studied treatments (Fig. 2).

When the daily N_2O emissions from the soil with high fertility level were at their highest, the soil of the two treatments with nitrogen fertilizer (fertilizer and fertilizer + biochar) was daily emitting significantly more ($p < 0.005$) N_2O than the same soil of the two treatments without the fertilizer which was not the case for the soil with medium fertility.

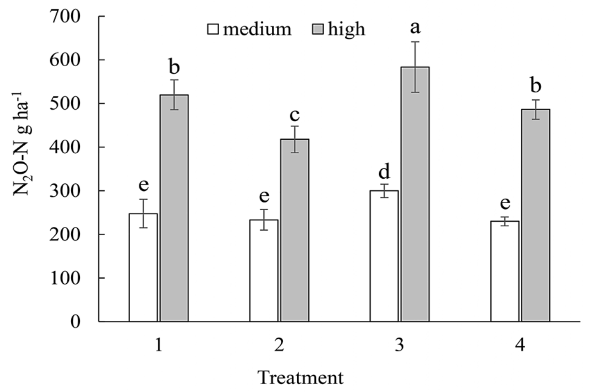
Cumulative N_2O fluxes from the soil with medium fertility for the whole period of measurements were 247.7 ± 56.7, 233.6 ± 41.2, 299.9 ± 26.6 and 229.9 ± 17.9 g ha^{-1} $N\text{-}N_2O$ in the control, biochar, fertilizer and biochar + fertilizer treatments, respectively (Fig. 3). Some of the inter-treatment differences between the cumulative fluxes from this soil were insignificant, but application of fertilizer resulted in a significantly higher ($p < 0.05$) cumulative N_2O flux from fertilizer treatment compared to the control and biochar treatments. Also the cumulative N_2O flux from fertilizer + biochar treatment was significantly lower ($p < 0.05$) compared to fertilizer treatment. The cumulative N_2O flux from the soil with fertilizer + biochar treatment did not differ significantly from that from the soil with control and biochar treatments. Cumulative N_2O fluxes from the soil with high fertility were 519.7 ± 37.2, 417.9 ± 33.7, 583.7 ± 71.2 and 486.2 ± 74.6 g ha^{-1} $N\text{-}N_2O$ for control, biochar, fertilizer and biochar + fertilizer treatments, respectively (Fig. 3). Cumulative N_2O fluxes from the soil with high fertility were significantly higher ($p < 0.005$) than those from the soil with medium fertility for all the treatments studied in the experiment.

For the soil with high fertility level the reduction in the cumulative N_2O flux after biochar application to the soil was statistically significant (control *vs* biochar treatments), unlike in the soil with medium fertility



Note. The bars indicate standard deviations from the means.

Figure 2. Daily nitrous oxide (N_2O) emissions from the soil with medium (A) and high (B) fertility for the control (1), biochar (2), fertilizer (3) and biochar + fertilizer (4) treatments



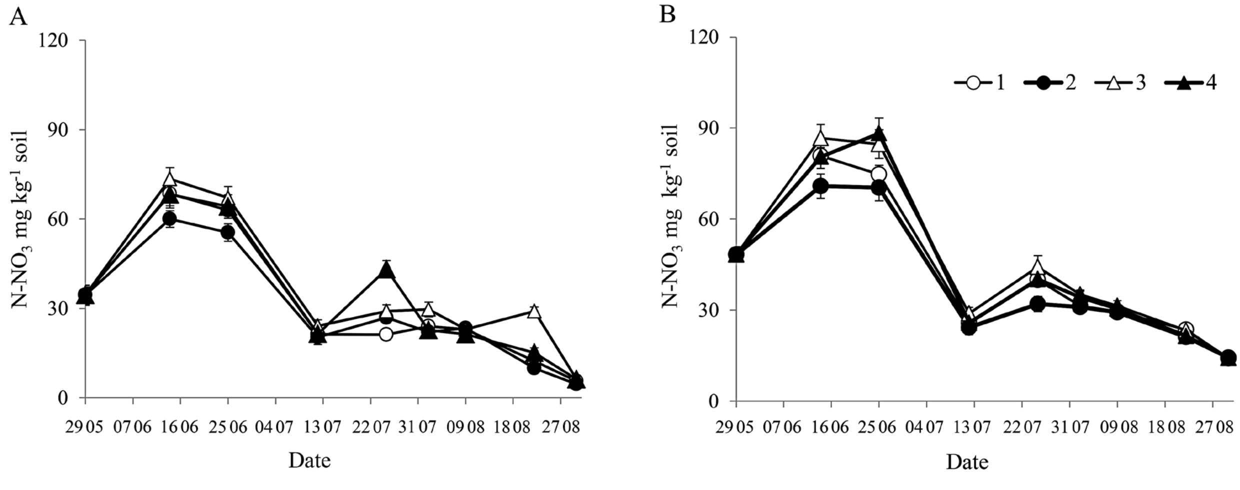
Note. The bars indicate standard deviations from the means; the letters (a, ab, b, c, d and e) indicate significant differences at $p < 0.05$ according to post-hoc Tukey's HSD test.

Figure 3. Cumulative nitrous oxide (N_2O) fluxes from the soil with medium and high fertility for the control (1), biochar (2), fertilizer (3) and biochar + fertilizer (4) treatments

level where the observed reduction was not statistically significant. Application of nitrogen fertilizer to the soil with high fertility level resulted in an increase of the cumulative N_2O flux, but the increase was not statistically significant, while in the soil with medium fertility it was. Application of biochar to the fertilized soil resulted in significant reduction of the N_2O cumulative flux (biochar + fertilizer *vs* fertilizer treatments).

For the soil with both fertility levels cumulative N_2O fluxes from the soil with fertilizer treatment were significantly higher ($p < 0.05$) than those from the soil with biochar and fertilizer + biochar treatments.

Dynamics of soil mineral nitrogen (N) content. Content of mineral N-NO_3^- in the soil with medium fertility during the period of studies varied from 5 to 73 mg kg^{-1} N soil, while in the soil with high fertility – from 14 to 88 mg kg^{-1} N soil for all the different treatments studied in the experiment (Fig. 4). The highest average content of mineral N-NO_3^- for all the different treatments in the soil with medium (65 mg kg^{-1} N soil) and high (79.6 mg kg^{-1} N soil) fertility was measured in June,



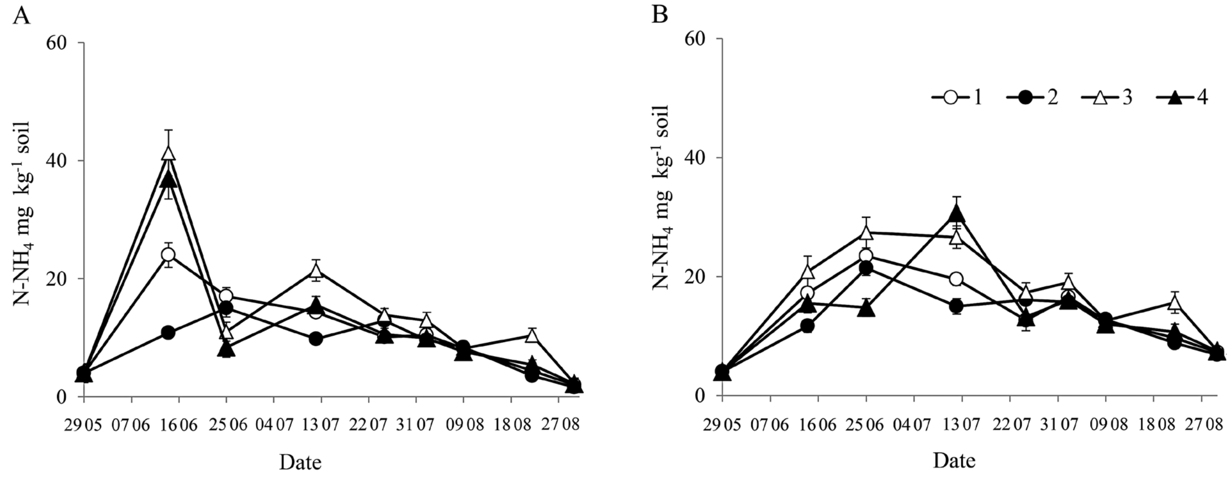
Note. The bars indicate standard deviations from the means.

Figure 4. Dynamics of mineral N-NO_3^- content in the soil with medium (A) and high (B) fertility for the control (1), biochar (2), fertilizer (3) and biochar + fertilizer (4) treatments

after the experiment was established. When the mineral N-NO_3^- content in both soils was at its highest, the soil with high fertility contained significantly more N-NO_3^- than the soil with medium fertility ($p < 0.001$). When mineral N-NO_3^- content fell to lower values in July and August, the difference between the soil with medium and high fertility (24.8 and 32.1 mg kg^{-1} N soil, respectively) was also statistically significant ($p < 0.001$). The lowest content of mineral N-NO_3^- was measured in both soils at the end of the experiment (11.2 and 18.3 mg kg^{-1} N soil for soils with medium and high fertility, respectively), and the difference between the two soils was also statistically significant.

For the soil with the same level of fertility most of the inter-treatment differences in the mineral N-NO_3^- content were statistically insignificant ($p < 0.001$) with an exception for the time, when the mineral N-NO_3^- content was at its highest and the lowest N-NO_3^- content was measured in the soil with biochar treatment for both fertility levels.

Soil mineral N-NH_4^+ content in the soil with medium fertility varied from 1.6 to 41 mg kg^{-1} N soil, while in the soil with high fertility it varied from 6.9 to 30.7 mg kg^{-1} N soil with the highest values measured in the second half of June early July and the lowest – at the end of the experiment (Fig. 5). Content of soil mineral N-NH_4^+ in the treatments without biochar as well as in the treatments with biochar was most of the time significantly higher ($p < 0.05$) in the soil with high than with medium fertility.



Note. The bars indicate standard deviations from the means.

Figure 5. Dynamics of mineral N-NH_4^+ content in the soil with medium (A) and high (B) fertility for the control (1), biochar (2), fertilizer (3) and biochar + fertilizer (4) treatments

Soil moisture content. During the experiment moisture content in the soil with medium fertility varied from 5.7% to 23.8%, while in the soil with high fertility – from 8.3% to 25.2% (Fig. 6). The lowest moisture content for the soil with both fertility levels was observed during the dry spell in the weather in early July. Most of the time moisture content in the soil with high fertility was significantly higher ($p < 0.05$) than that in the soil with medium fertility for all the treatments studied in the experiment. The only exception was the 12th of July, when the soils had the lowest moisture content in the season and the soil with high fertility was drier than the soil with medium fertility in the control and biochar treatments.

The seasonal average soil temperature was significantly lower for all the treatments for the soil with medium fertility compared to the soil with high fertility. The lowest difference in the seasonal average soil water content between the soils with medium and high fertility was found in the control treatment (2.15%). Application of fertilizer to the soils increased the difference to 4.0% and application of biochar with or without fertilizer – to 4.4% (Fig. 7).

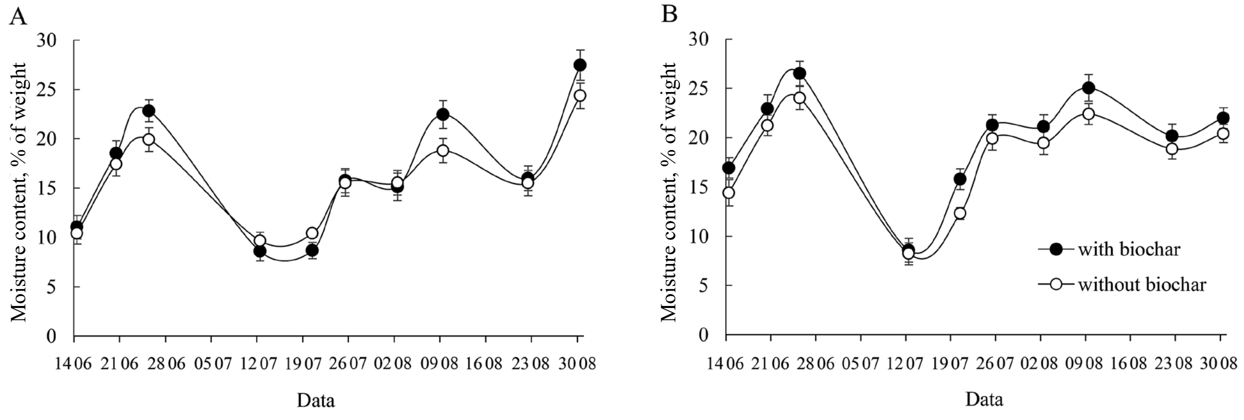
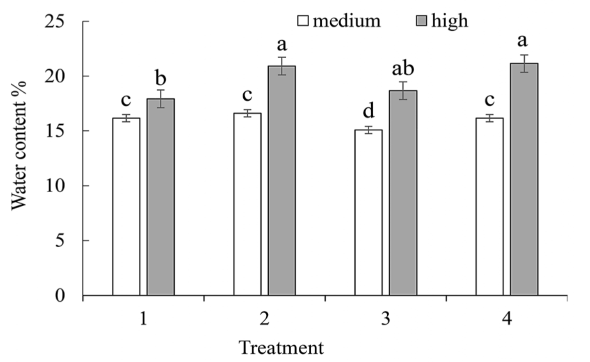


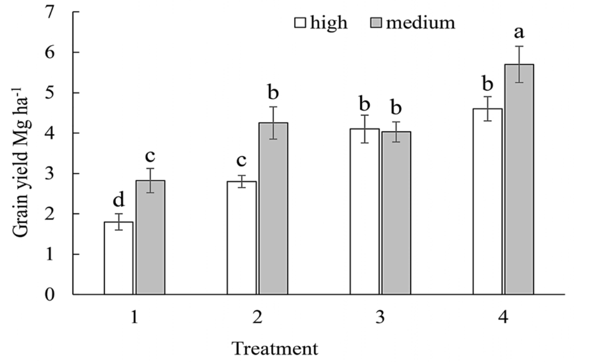
Figure 6. Dynamics of moisture content in the soil with medium (A) and high (B) fertility for the treatments with (biochar and biochar + fertilizer) and without (control and fertilizer) biochar



Note. The bars indicate standard deviations from the means; the letters (a, ab, b, c and d) indicate significant differences at $p < 0.05$ according to post-hoc Tukey's HSD test.

Figure 7. Seasonal average water content in the soil with medium and high fertility for the control (1), biochar (2), fertilizer (3) and biochar + fertilizer (4) treatments

Barley yield. Grain yields of spring barley harvested from the soil with medium fertility were significantly lower than those from the soil with high fertility for all the studied treatments, except fertilizer treatment. Biochar, fertilizer and biochar + fertilizer treatments resulted in significantly higher ($p < 0.05$) yields than control treatment for the soil with both fertility levels (Fig. 8).



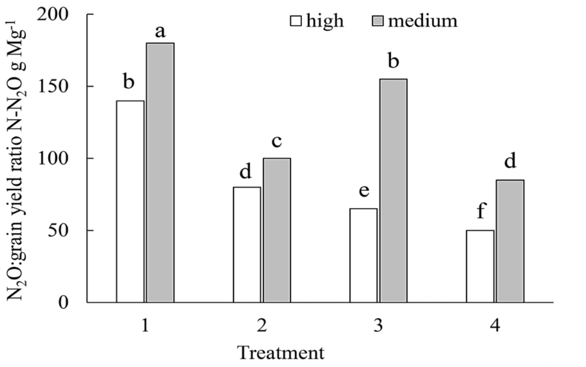
Note. The bars indicate standard deviations from the means; the letters (a, b, c, d and e) indicate significant differences at $p < 0.05$ according to post-hoc Tukey's HSD test.

Figure 8. Grain yields of spring barley for the soil with medium and high fertility for the control (1), biochar (2), fertilizer (3) and biochar + fertilizer (4) treatments

The grain yields of spring barley depended on the soil treatment and increased in the following order: control < biochar < fertilizer = biochar + fertilizer for the soil with medium fertility and control < biochar = fertilizer < biochar + fertilizer for the soil with high fertility.

N_2O cumulative emission as function of grain yield of spring barley. In order to provide a better assessment of soil N status and efficiency of agricultural measures in the mitigation of gaseous N losses from soils, several researchers used yield-scaled N_2O emissions, i.e. ratios of N_2O cumulative fluxes to grain yields or aboveground dry biomass of plants (Van Groenigen et al., 2010; Halvorson et al., 2011; Venterea et al., 2011).

The yield-scaled N_2O emissions of spring barley for our experiment are presented in Figure 9. They were higher for the soil with high than with medium fertility for all the studied treatments. For both soils the highest yield-scaled N_2O emissions were observed in the control treatment and the lowest – in the biochar + fertilizer treatment. The biochar, fertilizer and biochar + fertilizer treatments resulted in lower yield-scaled N_2O emissions compared to the control treatment for the soil with both fertility levels.



Note. The letters (a, b, c, d and e) indicate significant differences at $p < 0.05$ according to post-hoc Tukey's HSD test.

Figure 9. The yield-scaled N_2O emissions for the soil with medium and high fertility for the control (1), biochar (2), fertilizer (3) and biochar + fertilizer (4) treatments

Discussion

Effect of soil management and biochar application on soil water content. Application of biochars to soils is reported to result in an improvement of their physical properties, particularly of water-holding capacity, due to biochar's porous structure with high specific surface area and affinity to water (Glaser et al., 2002; Kolb et al., 2009; Van Zwieten et al., 2010 a).

The results of our studies showed that initial difference in the soil fertility had a significant effect on the average seasonal soil water content. The soil with high fertility in average contained more water than the soil with medium fertility in the field conditions most of the growing season. It might be the result of higher water-holding capacity of the soil organic matter in the high fertility soil as well as of higher soil capillary porosity resulting from higher organic matter content (Lehmann et al., 2011).

Application of the biochar at a rate of 12 t ha^{-1} significantly increased the water content of the soil with high fertility but not of the soil with medium fertility for most of the growing season. The significant increase in soil water content with biochar application is in agreement with the studies of Glaser et al. (2002) who reported that incorporation of biochar at a rate of 15% of soil volume increased the water-retention capacity of light-textured soils by 18%. Woolf (2008) in his review has also shown that the water content of light-textured soils after biochar application was more often increasing than that of heavy soils as the mineral phase of the latter can hold substantial quantities of water unlike sandy particles of light-textured soils. The results of our experiment also demonstrate that the soil fertility can affect the way the biochar is affecting the soil water content of the light-textured soil studied in our experiment. Rizhiya et al. (2015) have shown for the same soil that the increase of the water-retention for the soil with medium fertility after biochar incorporation was lower (5%) than that for the soil with high (9%) fertility at a range of soil moisture potentials from −5 to −50 kPa. It was also shown that the application of biochar to the soil with high fertility resulted in significantly lower shrinkage of the soil compared to the soil with medium fertility after three cycles of saturation and drying, and the soil with high fertility had higher capillary porosity than the soil with medium fertility. Biochars usually have specific bulk densities from 1.5 to 2.1 g cm^{-3} (Brewer et al., 2009). The soil with medium and high fertility had specific bulk density 2.63–2.65 and 2.55–2.57 g cm^{-3}, respectively. It is known that the force producing shrinkage is a surface tension at the air-water-solid phase interfaces. At the beginning of the process, shrinkage occurs in a proportion of water removed. Then a point is reached at which interactions between particles of the solid phase arise. A further shrinkage is defined by the degree of compression and re-orientation of particles as a result of the increased surface tension at the solid phase-water interfaces. Therefore, in the soil with medium fertility, compared to that with high fertility, there were weaker repulsive interactions between the soil mineral and biochar particles which during drying-induced compression could be in a closer packing. The above-mentioned changes in the soil physical properties induced by biochar application could also be the reason for greater water content during the growing season of 2012 in the soil with high fertility than in the soil with medium fertility.

Effect of soil management and biochar on soil mineral nitrogen (N). Accumulation of nitrates, which is the result of the process of nitrification, was higher at the beginning of our field studies and the rate of nitrification was greater in the soil with high than with medium fertility in all the treatments. That could be a result of higher mineral N content in the soil with high fertility as well as of higher microbial activity of the soil which was shown for the same soil by Rizhiya et al. (2011).

According to our research data, nitrification activity in biochar treatment was the lowest for the soil with both fertility levels compared to that in the other three treatments for the first half of the growing season. It is in agreement with Novak et al. (2010) who reported that the application of pecan-shell biochar at rates of 5–20 g kg^{-1} into Norfolk loamy sand resulted in an immobilization of NO_3^- and in its reduced availability for cereal plants. In the second half of the growing season the mineral nitrate content in the soils of all the treatments decreased with the plant growth and the difference in nitrate concentration between the different treatments became less pronounced, but still the soil with high fertility always contained significantly more nitrates than the soil with medium fertility.

Ammonium accumulation in the soil can be partly a result of denitrification and in our experiment N-NH_4^+ was also introduced to the soil with mineral N-fertilizer. Still soil N-NH_4^+ concentrations were higher in the soil with high fertility indicating that process of denitrification might be going on in this soil together with the process of nitrification. The possibility of the two processes developing in different areas of the same soil at the same time is accepted now (Wrage et al., 2001).

Biochar has a high affinity to NH_4^+ and can easily absorb it (Lehmann et al., 2011). The results of our studies showed that biochar treatment resulted in 20.0% and 8.1% average reduction in mineral N-NH_4^+ concentrations in the soil with medium and high fertility, respectively, compared to control treatment. However, the average N-NH_4^+ content in the biochar + fertilizer treatment exceeded its average concentration in the control treatment by 6.7% and 1.5% in the soil with medium and high fertility, respectively. Therefore, the application of biochar to the studied soils together with nitrogen fertilizer seems to be a better way to avoid the available mineral N deficiency which can be observed if only biochar is incorporated into this soil.

Effect of soil management and biochar on nitrous oxide (N_2O) flux. Cumulative N_2O fluxes from the soil with high fertility in our experiment were significantly higher than those from the soil with medium fertility for all the treatments of the experiment. It is in agreement with the results of many experiments (Broucek, 2017) showing that application of farmyard manure to the soils resulted in high N_2O fluxes due to application of available N and C and microbial C, despite the reduction in soil bulk density and improved soil aeration. The availability of N and C, combined together with the higher moisture content had a greater influence on N_2O emission from the soil with high fertility than the fact that the soil had lower bulk density and higher porosity than the soil with medium fertility.

One of the key reasons for the application of biochar in agriculture is the mitigation of N_2O emissions from soils. A decrease in N_2O emission from agricultural soils was often observed after application of biochar of different origin (Yanai et al., 2007; Singh et al., 2010; Van Zwieten et al., 2010 b; Buchkina et al., 2019). Van Zwieten et al. (2010 b) reported that an application of the green-waste-derived biochar into an acidic *Ferrosol* improved its porosity and aeration, and as a result led to a decreased denitrification and N_2O emission. According to our data, application of biochar to the soil with medium fertility did not result in any reduction of cumulative N_2O flux from this soil. These results are in agreement with the studies that found little reductions of N_2O fluxes from soils by biochar without mineral N application (Zhang et al., 2010) and supply of available organic C (Felber et al., 2012).

For the biochar and biochar + fertilizer treatments for the soil with high fertility as well as for biochar + fertilizer treatment for the soil with medium fertility the effect of biochar application on N_2O flux mitigation was statistically significant. These results confirm the data of other researchers who found substantial reductions of N_2O emission after biochar application in the order of up to 70% in the fertilized treatments (Singh et al., 2010; Zhang et al., 2010).

Our previous results of laboratory experiments with the same soils (Rizhiya et al., 2015) showed that the incorporation of biochar at a rate of 380 kg ha^{-1} into the soils with medium and high fertility caused insignificant changes in cumulative N_2O fluxes, when biochar was applied to the soil without a source of mineral N. However, the combined application of biochar and red clover residues (600 kg ha^{-1}) into both soils resulted in lower N_2O cumulative emissions than those from the treatment with red clover residues. These data are complementing our findings from the present small-scale field experiment that application of biochar to soils can contribute to N_2O flux mitigation only if soils are rich in available mineral N and organic C.

N_2O cumulative emission as function of grain yield of spring barley. Halvorson et al. (2011) reported that the yield-scaled N_2O emissions ranged from 15 (no N added) to 121 (urea added) g Mg^{-1} N_2O-N grain yield. For the soil with medium fertility in our experiment the yield-scaled N_2O fluxes ranged in a decreasing order: 138 (control), 81 (biochar), 72 (fertilizer) and 50 (biochar + fertilizer) g Mg^{-1} N_2O-N grain yield. The N use efficiency in the soil with medium fertility was increasing in fertilizer and biochar + fertilizer treatments. The soil with high fertility demonstrated a slightly different decreasing order of the yield-scaled N_2O emissions: 182 (control), 156 (fertilizer), 98 (biochar) and 84 (biochar + fertilizer) g Mg^{-1} N_2O-N grain yield. In contrast to the soil with medium fertility, the application of 90 kg ha^{-1} N with mineral fertilizer to this soil resulted in a lower decrease in the yield-scaled N_2O emissions compared to the control due to higher N_2O cumulative flux from this soil and no changes in barley yield after fertilizer application. According to several authors, there is a threshold of N rates which can exceed N requirements of crops (Granli, Bockman, 1994). If the N rates exceed the crop N requirements, N_2O emissions from soils can become more variable and drastically increase (Snyder et al., 2009; Hoben et al., 2011). It might be that 90 kg ha^{-1} N of ammonium nitrate, applied to the soil with high fertility could exceed the soil N requirements of spring barley and cause increased N_2O emissions.

Conclusions

1. Significant changes in water-holding capacity and the amount of available nitrogen (N) occurred in loamy sand *Stagnic Luvisol* with high fertility which resulted from the application of high rates of farmyard manure during the previous 10 years, and thus it emitted significantly more nitrous oxide (N_2O) over a growing season than the soil with medium fertility.

2. Biochar application effect on N_2O emissions depended on the relatively short soil management history and was reducing the emission from the soil with high fertility rich in mineral N and C but not from the soil with medium fertility if no nitrogen fertilizer was applied to the latter soil.

3. Yield-scaled N_2O emissions were the highest from the control treatments for the soil with both studied fertility levels, and the soil with high fertility was always characterized by higher yield-scaled N_2O emissions than the soil with medium fertility.

4. Application of biochar to the soil with both studied fertility levels with or without fertilizer reduced yield-scaled N_2O emissions showing that biochar application to the soils can facilitate N use by the plants.

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Medžio anglies įtaka N_2O emisijai, augalų derliui ir stagninio išplautžemio savybėms lauko eksperimente

E. Y. Rizhiya[1], I. M. Mukhina[1], E. V. Balashov[1], V. Šimansky[2], N. P. Buchkina[1]

[1]Rusijos agrofizinių tyrimų institutas
[2]Slovakijos žemės ūkio universiteto Agrobiologijos ir maisto išteklių fakultetas

Santrauka

Dirvožemis yra vienas pagrindinių azoto oksido (N_2O) emisijos šaltinių žemės ūkyje. Jo naudojimo būdai gali reikšmingai paveikti N_2O emisiją pakeisdami dirvožemio fizikines, chemines ir biochemines savybes. Medžio anglies panaudojimas dirbamuose dirvožemiuose yra vienas iš būdų siekiant sumažinti N_2O emisiją, tačiau medžio anglies įtaka gali būti nevienoda dirvožemiams, kurie skiriasi derlingumo lygiu. Tyrimo tikslas – įvertinti medžio anglies įtaką N_2O emisijai, dirvožemio savybėms ir miežių derliui didelio ir vidutinio derlingumo rišlaus smėlio stagniniame išplautžemyje, kuris susidarė per 10 metų laikotarpį tręšiant didelėmis normomis mėšlo ir mineralinių trąšų. Eksperimentas buvo atliktas 2012 m. vegetacijos laikotarpiu šiaurės vakarų Rusijoje. Jį sudarė 4 variantai: 1) kontrolinis (be medžio anglies, be N trąšų), 2) medžio anglis (12 t ha^{-1}), 3) N trąšos (90 kg ha^{-1} N) ir 4) medžio anglis (12 t ha^{-1}) + N trąšos (90 kg ha^{-1} N); 5 pakartojimai. Reikšmingi vandentalpos ir augalų pasisavinamo azoto (N) kiekio pokyčiai įvyko didelio derlingumo dirvožemyje, todėl per vegetacijos laikotarpį N_2O emisija iš šio dirvožemio buvo reikšmingai didesnė nei iš vidutinio derlingumo dirvožemio. Medžio anglies įtaka N_2O emisijai priklausė nuo dirvožemio naudojimo istorijos – medžio anglis mažino emisiją iš derlingo dirvožemio, turinčio daug mineralinio N ir C, tačiau ji nemažino emisijos iš vidutinio derlingumo dirvožemio, jeigu jis nebuvo tręštas azotu. Priklausomai nuo derliaus dydžio, N_2O emisija buvo didžiausia kontroliniuose variantuose, o N_2O emisija, perskaičiuota pagal derliaus dydį, buvo didesnė didelio derlingumo dirvožemyje nei vidutinio derlingumo.
Medžio anglies naudojimas sumažino N_2O emisiją, priklausomai nuo derliaus dydžio, iš vidutinio ir didelio derlingumo dirvožemio; tai rodo, kad medžio anglis gali pagerinti augalų azoto įsisavinimą.

Reikšminiai žodžiai: bioanglis, dirvožemio derlingumas, dirvožemio savybės, N_2O emisija, pagal derliaus dydį perskaičiuota emisija.