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Short-term effect of heavy precipitation on nutrient leaching from arable sandy loam soil amended with fertiliser and biochar

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The authors of the article disassociate themselves from the Russian politics.

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Abstract

The purpose of this study was to assess the effect of biochar application on the leaching of the main nutrients from the topsoil of the arable sandy loam soil (*Albic Luvisol*) of North-Western Russia after application of mineral fertiliser in the conditions of heavy precipitation. A short-term laboratory experiment included 6 treatments: (1) without fertiliser and biochar (control), (2–3) soil + biochar (10 and 20 t ha^{-1}), (4) soil + fertiliser, and (5–6) soil + biochar (10 and 20 t ha^{-1}) + fertiliser. During the experiment, the soil in the cylinders was watered three times with high rates (345 cm^3) of distilled water, corresponding to the maximum amount of daily precipitation (44 mm) observed in the natural conditions of the area. The leachate was collected (on the 1st, 2nd and 5th day of the experiment) and tested for pH_{H2O}, available nitrogen ($N\text{-}NO_3^-$, $N\text{-}NH_4^+$), phosphorus (P_2O_5) and potassium (K_2O). At the end of the experiment, separate soil samples were formed of the upper 8-cm and lower 4-cm soil layers in the cylinders. The pH_{H2O} values, concentrations of $N\text{-}NO_3^-$, $N\text{-}NH_4^+$, P_2O_5 and K_2O were determined in the samples. The results showed that the effect of biochar on the movement and accumulation of the main available nutrients in the soil after fertiliser application and under the effect of heavy precipitation was more pronounced at the higher biochar application rate of 20 t ha^{-1}. Biochar application reduced the acidity of the leachate and the soil not only in the layer, where the biochar had been applied, but also in the lower layer affected by the leachate. Available $N\text{-}NH_4^+$, P_2O_5, and K_2O were retained in the soil through biochar application for a short period of time, while $N\text{-}NO_3^-$ leaching was not affected. Overall, biochar can be used as a soil ameliorant, as even a short delay in the nutrient leaching is potentially beneficial to nutrient utilization of crops.

Keywords: biochar, mineral fertiliser, nutrients, leachate, soil, precipitation.

Introduction

Leaching of nutrients from arable soils can deplete soil fertility, increase fertiliser costs, reduce crop yields and pose a threat of environmental pollution (Hester et al., 1996; Ju et al., 2006; Cameron et al., 2013; Watanabe et al., 2018). Therefore, a very important area of research is the development of effective ways to retain nutrients in soils. One of such methods could be application of biochar to agricultural soils.

Biochar is an organic material that has been heat treated in airless conditions. It can be obtained from a wide range of carbon-rich materials such as grasses, hardwoods, softwoods, agricultural and forestry residues. The use of biochar in agriculture is becoming more widespread as a way to regulate soil moisture content, particularly in coarse-textured soils (Buchkina et al., 2017; Igaz et al., 2018; Razzaghi et al., 2020), to reduce greenhouse gas emissions into the atmosphere, mainly N_2O and sometimes CO_2 and CH_4 (He et al., 2017; Buchkina et al., 2019) and to control the mobility of various environmental pollutants (Wang et al., 2020). In addition, it is suggested that biochar application to soils can increase their fertility and crop productivity by reducing leaching or even supplying plants with nutrients (Yao et al., 2012).

The soil type and biochar properties are affecting the way biochar influences soil nutrient losses and retention. Laird et al. (2010) studied nutrient leaching from the soil after application of manure and various rates of biochar. These studies have shown that with an increase in the rate of biochar there was a significant decrease in nitrogen and phosphorus leached from the soil, despite the fact that significant amount of these elements was introduced into the soil with the biochar. Yao et al. (2012) have shown in the leaching experiment that some of the studied biochars were effectively reducing the total amount of nitrates, ammonium and phosphates in the filtrate, while the others reduced the leaching of nitrates and ammonium but caused additional release of phosphates from the soil. Biederman and Harpole (2013) used a meta-analysis to conduct the first quantitative

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review of data from 371 independent studies on biochar applications. It was found that, despite the variability caused by soil properties and climate, the addition of biochar resulted in a significant increase in the content of total phosphorus, available potassium, total nitrogen and total carbon in the soil compared with the control conditions. After the addition of biochar, soil acidity (pH) also generally increased. Parameters that did not show a significant response to biochar application included content of available phosphorus and nitrogen in the soil. Bu et al. (2017) in a leaching experiment have found that increasing levels of biochar resulted in decreasing cumulative amounts of leached nitrates, ammonium and dissolved organic nitrogen but in increasing leaching of available phosphorus. It can be concluded that biochar application to soils can be an effective way to control nutrient leaching in agricultural production. However, the impact of biochar on nutrient leaching from soils is ambiguous and varies depending on the time scale, type of biochar and nutrients.

To date, there is still not enough information available on the subject of short-term effect of biochar on the mobility of nutrients in agricultural soils, particularly immediately after fertiliser application to the soil, when the nutrients are prone to leaching in the conditions of heavy rain. This is important for the provision of nutrients to growing plants and microorganisms, and it is also important for addressing the issue of biochar's ability to influence the leaching or redistribution of nutrients in the soil at the very early stage after fertiliser application.

The purpose of this study was to assess the effect of biochar on the leaching of the main nutrients from the arable horizon of sandy loam soil (*Albic Luvisol*) of North-Western Russia straight after application of mineral fertiliser under heavy precipitation. The hypothesis of the experiment was that biochar application would affect the nutrient movement / retention within the soil not only in the layer of application but also in the lower layer.

Materials and methods

The soil material of the upper horizon (0–23 cm) of the arable sandy loam soil (*Albic Luvisol*) (WRB, 2014) of North-Western Russia (Table 1) was collected in the field, dried and sieved through a 2-mm sieve in the autumn of 2017. Cylinders with a volume of 940 cm^3, surface area of 78.5 cm^2 and a height of 12 cm were used for the laboratory experiment.

Table 1. Initial properties of the sandy loam soil (*Albic Luvisol*) used in the experiment

Field capacity %	Bulk density g cm^{-3}	Soil pH_{KCl}	C_{tot} %	N_{tot} %	N_{min} mg kg^{-1}	P_2O_5 mg kg^{-1}	K_2O mg kg^{-1}
20	1.3	6.3	1.9	0.14	15.7	237	131

C_{tot} – total carbon, N_{tot} – total nitrogen, P_2O_5 – available phosphorus, K_2O – available potassium

The experiment included 6 treatments: 1) without fertiliser and biochar – control (C); 2) soil + biochar (10 t ha^{-1}) (SB10); 3) soil + biochar (20 t ha^{-1}) (SB20); 4) soil + fertiliser (120 kg ha^{-1} N, 135.2 kg ha^{-1} P, 259 kg ha^{-1} K) (SF); 5) soil + fertiliser (120 kg ha^{-1} N, 135.2 kg ha^{-1} P, 259 kg ha^{-1} K) + biochar (10 t ha^{-1}) (SFB10); 6) soil + fertiliser (120 kg ha^{-1} N, 135.2 kg ha^{-1} P, 259 kg ha^{-1} K) + biochar (20 t ha^{-1}) (SFB20), replicated four times.

According to the experiment design, the soil (628 g) for the upper 8-cm cylinder was mixed with biochar (7.85 g or 15.7 g for the rates of biochar 10 or 20 t ha^{-1}, respectively) and/or with fertiliser (0.942 g) or was left without any amendment (control). The soil (314 g) for the lower 4-cm cylinder was left unamended. The main reason, why the soil was mixed with the biochar only in the upper 8-cm layer, was that after surface application of biochar in the field only shallow cultivation (8–10 cm deep) was used to mix the biochar with the soil. The experiment partly mimicked this situation, but also the purpose of the study was to learn whether surface application of biochar had an effect on nutrient distribution in the lower part of the plough layer, where the biochar was not initially applied.

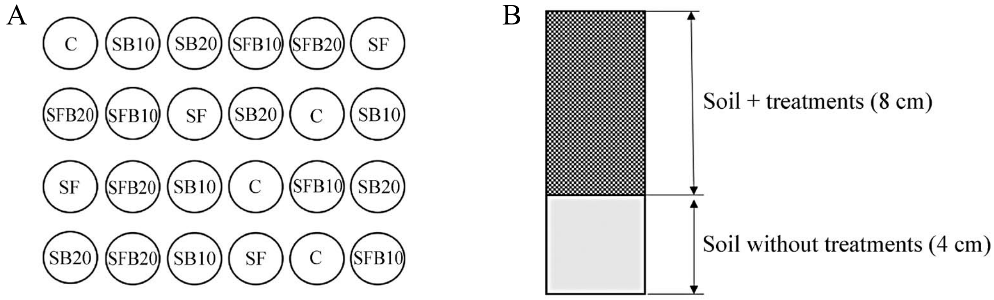
The short-term laboratory experiment was conducted at an average air temperature of 20°C and an average air humidity of 30%. A fine fraction (<1 mm) of slow pyrolysis biochar produced by "Firewood" company from the wood of broad-leaved trees at final temperature 550–650°C and complex mineral fertiliser: $(NH_4)_2SO_4$ + $(NH_4)_2HPO_4$ + K_2SO_4 with concentrations of N – 12%, P – 15%, K – 15%, were used (Table 2).

Table 2. Chemical properties of the biochar used in the experiment

C_{tot} %	N_{tot} %	H %	O %	C:N	H:C	O:C	Soil pH	Water %	Ash %	Surface area m^2 g^{-1}	Porosity %
78.6	0.3	5.2	4.2	302	0.06	0.05	7.2	3.92	21.4	16.2	81

C_{tot} – total carbon, N_{tot} – total nitrogen, H – hydrogen, O – oxygen

The bulk density of the soil in all the cylinders was 1.3 g cm^{-3}, which was an average bulk density of the topsoil in the field conditions. The cylinders with the soil were filled in accordance with the different treatments, weighed and left to stabilize for 5 days with the soil water content kept at the field capacity level (20%) gravimetrically. During the experiment, the soil in the cylinders was watered 3 times on the 1st, 2nd and 5th day after the soil stabilization with high rates of distilled water (345 cm^3) corresponding to the maximum amount of daily precipitation (44 mm) observed in the natural conditions of the area. The leachate was collected three times and was tested for soil acidity (pH) using the potentiometric method, available nitrogen in ammonium form ($N\text{-}NH_4^+$) using Nessler reagent and in nitrate form ($N\text{-}NO_3^-$) using the photometric method, available potassium (K_2O) using the atomic absorption spectrometry and available phosphorus (P_2O_5) using the photometric method. At the end of the experiment, the cylinders were disassembled. In the cylinders, the upper 8-cm and lower 4-cm soil layers were processed as separate samples. The soil samples were dried, and the acidity (pH_{H2O}) values as well as the concentration of N-NH_4^+, N-NO_3^-, P_2O_5 and K_2O were determined in the samples according to the same methods as in the leachate. Daily and average (for 3 days) values of leachate pH, daily and total (for 3 days) concentrations of N-NH_4^+, N-NO_3^-, P_2O_5 and K_2O in the leachate and the soil characteristics at the end of the experiment were used.



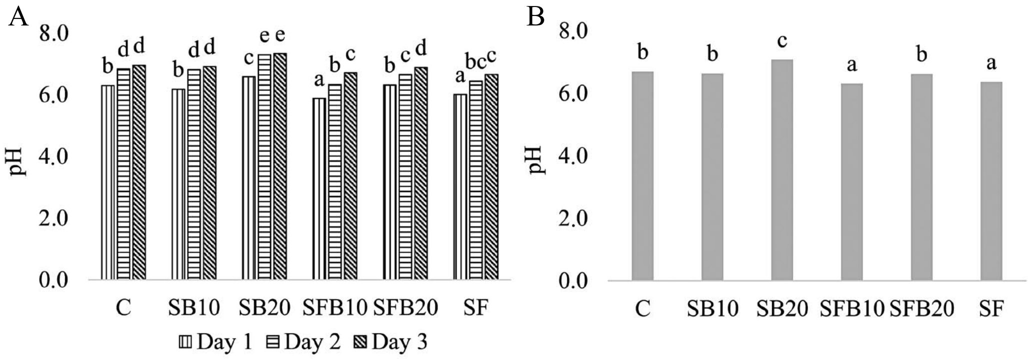
C – control treatment, SB10 – soil + biochar (10 t ha^{-1}), SB20 – soil + biochar (20 t ha^{-1}), SF – soil + fertiliser (120 kg ha^{-1} N, 135.2 kg ha^{-1} P, 259 kg ha^{-1} K), SFB10 – soil + fertiliser (120 kg ha^{-1} N, 135.2 kg ha^{-1} P, 259 kg ha^{-1} K) + biochar (10 t ha^{-1}), SFB20 – soil + fertiliser (120 kg ha^{-1} N, 135.2 kg ha^{-1} P, 259 kg ha^{-1} K) + biochar (20 t ha^{-1})

Figure 1. The experimental design (A) and the experimental column structure (B)

To find out whether the obtained results were normally distributed and as the distribution was not normal, the Shapiro-Wilk test was used. For the data analysis, the nonparametric statistics were used: Kruskal-Wallis test and Mann-Whitney U test. To find out whether the groups of data obtained at the different treatments (for all the studied parameters) were in some way the same, Kruskal-Wallis test was used. If this test was showing that some groups of data were different, then Mann-Whitney U test was used to find out the significance of differences between pairs of data sets, which were falling in different groups based on the results of Kruskal-Wallis test.

Results

Leachate from the soil of the experimental treatments was slightly acidic to neutral and had daily acidity (pH_{H2O}) values between 5.9 and 7.3. For all the experimental treatments, the lowest pH_{H2O} values were measured in the leachates of the 1st day, while the highest – in the leachate of the 5th day of the experiment (Figure 2A). The leachate from the control treatment had pH_{H2O} average values close to 6.7, and application of 10 t ha^{-1} of biochar to the unfertilised soil did not change the value significantly. Application of 20 t ha^{-1} of biochar to the unfertilised soil resulted in a significant increase (to 7.1), while application of the fertiliser resulted in a significant decrease (to 6.4) of the pH_{H2O} average value. Application of 10 t ha^{-1} of biochar to the fertilised soil did not significantly increase the leachate pH_{H2O} value, while application of 20 t ha^{-1} of biochar to the fertilised soil resulted in the leachate pH_{H2O} value close to that of the water collected from the control treatment (Figure 2B).

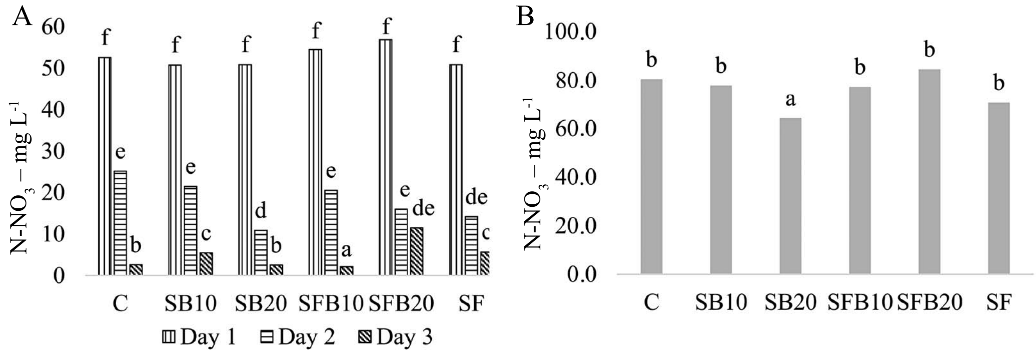


Note. Explanation under Figure 1; the results with the same letter were not significantly different at $p < 0.05$.

Figure 2. Daily (A) and 3 days average (B) values of the soil leachate acidity (pH)

The daily pattern of N-NO_3^- leaching from the soil of all the experimental treatments was the same with the significantly highest amount of N-NO_3^- leached on the 1st day: 65–80% of the total (Figure 3A). On the 2nd and the 5th day of the experiment, the amount of leached N-NO_3^- was 17–30% and 3–14% of the total, and the difference between the 2nd and the 5th days was also significant in most of the cases. The application of the complex mineral fertiliser did not increase, and the application of biochar into the fertilised soil did not reduce the total amount of N-NO_3^- leached from the soil significantly. The only significant change in this parameter was the reduction in the total amount of N-NO_3^- leached from the soil with 20 t ha^{-1} of biochar compared to all the other treatments (Figure 3B).

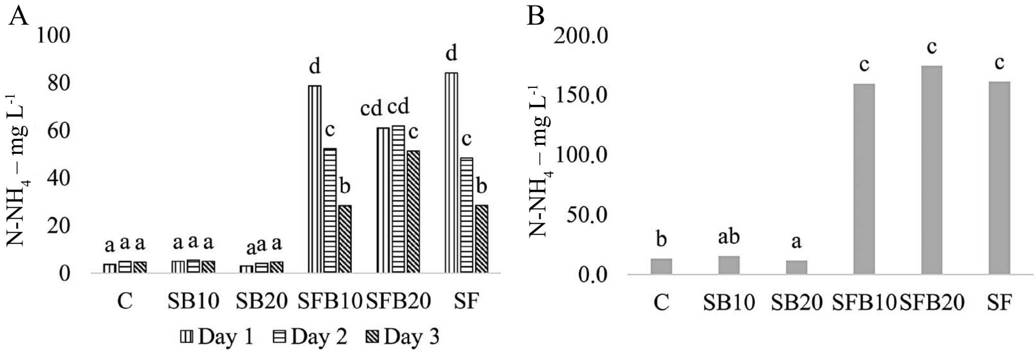
The fertiliser application had a significant effect on the daily and total amount of N-NH_4^+ leached from the soil: it was at least 10 times higher in the leachate from the fertilised soil compared to that from the unfertilised one (Figure 4A). The amount of N-NH_4^+ leached from the unfertilised soil in different days was very low with no significant differences between the days. For the fertilised soil of SF and SFB10 treatments, the highest amount of N-NH_4^+ was leached on the 1st day and the lowest – on the 5th day. For the soil of SFB20 treatment, leaching was more even, and the differences in the amount of N-NH_4^+ leached from the soil in different days were not significant. At the same time, the amount of N-NH_4^+ leached on the 1st day was significantly lower, and



Note. Explanation under Figure 1; the results with the same letter were not significantly different at $p < 0.05$.

Figure 3. Daily (A) and the total amount (B) of available nitrate nitrogen ($N\text{-}NO_3^-$) leached from the soil in 3 days

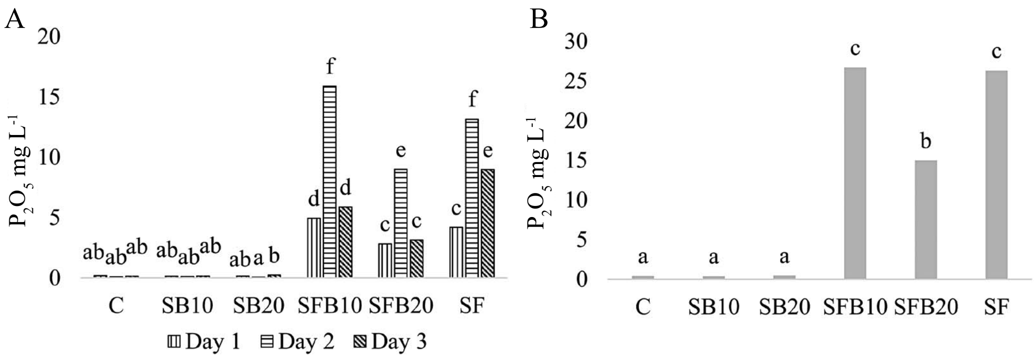
on the 5th day – significantly higher compared to the same days for the soil of SF and SFB10 treatments. Application of either rate of biochar did not significantly change the total amount of $N\text{-}NH_4^+$ leached from the fertilised soil (Figure 4B).



Note. Explanation under Figure 1; the results with the same letter were not significantly different at $p < 0.05$.

Figure 4. Daily (A) and the total (B) amount of available ammonium nitrogen ($N\text{-}NH_4^+$) leached from the soil in 3 days

Application of the complex fertiliser significantly increased the daily and total amount of P_2O_5 leached from the soil (Figure 5). The daily patterns of P_2O_5 leaching were quite similar for the soil of all the fertiliser treatments: significantly higher amount (around 60%) of P_2O_5 was leached on the 2nd day, while on the 1st and the 5th day, the amounts were similar (20% of the total). The only exception was SF treatment, where P_2O_5 loss with the leachate on the 5th day was significantly higher (25% of the total) than on the 1st day (15% of the total). The total loss of P_2O_5 from the soil without fertiliser was 0.5 mg L^{-1} P_2O_5 or less, while in the fertilised soil it was 15–26 mg L^{-1} P_2O_5. Losses of P_2O_5 from the unfertilised soil were very low and did not change significantly after biochar application in either rate. Despite the similarities in the daily pattern of P_2O_5 loss, there was a significant reduction in the total amount of P_2O_5 washed out with the leachate from the soil of SFB20 treatment: the total loss was almost twice lower compared to SF and SFB10 ones.

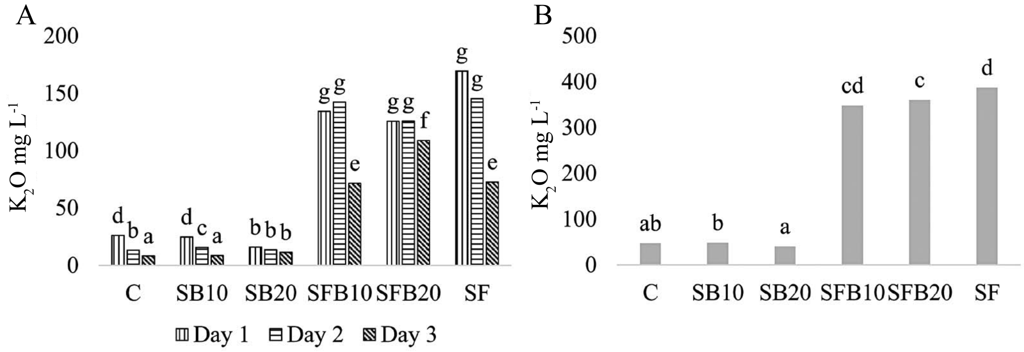


Note. Explanation under Figure 1; the results with the same letter were not significantly different at $p < 0.05$.

Figure 5. Daily (A) and the total (B) amount of available phosphorus (P_2O_5) leached from the soil in 3 days

The fertiliser application significantly increased the daily and total amount of K_2O leached from the soil: the latter was 7–8 times higher compared to the unfertilised treatments (Figure 6). For most of the treatments, the maximum amount of K_2O was leached on the 1st day and the lowest – on the 5th day. Application of biochar at both rates to the fertilised soils did not result in any significant reduction of K_2O loss with the leachate neither on the 1st nor on the 2nd day (Figure 6A). In the unfertilised soil, biochar was effectively reducing K_2O

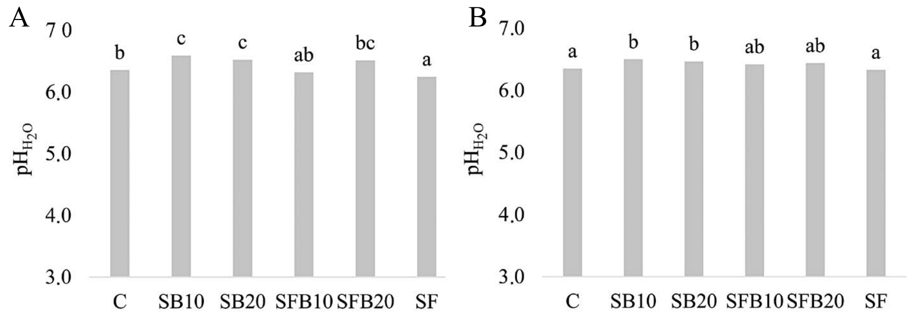
loss on the 1st day but only at the rate of 20 t ha^{-1}. At the same time, the reduction was not very high, as the initial K_2O content was also quite low. The total loss of K_2O from the fertilised soil was significantly lower only at the biochar rate of 20 t ha^{-1} (Figure 6B).



Note. Explanation under Figure 1; the results with the same letter were not significantly different at $p < 0.05$.

Figure 6. Daily (A) and the total (B) amount of available potassium (K_2O) leached from the soil in 3 days

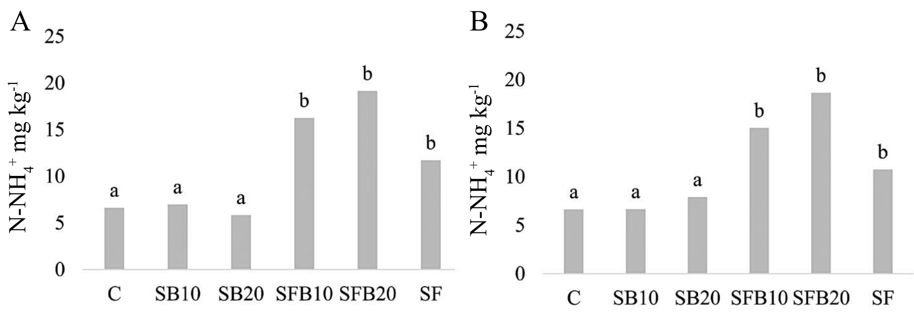
Soil acidity. After the leaching experiment, the soil acidity (pH_{H2O}) values of the upper 8-cm layer (where the biochar and fertiliser had been applied) were significantly different between the experimental treatments (Figure 7). The lowest value (6.25) was found in the soil after fertiliser application. The soil of the control, SFB10 and SFB20 treatments had similar average pH_{H2O} values (6.36, 6.32 and 6.51, respectively), while the soil of SB10 and SB20 ones had the highest pH_{H2O} values, which were significantly higher than in all the other treatments. The pH_{H2O} values of the lower 4-cm soil layer (where no biochar or fertiliser had been applied) also changed as a result of the leaching experiment, but the differences between the treatments were much smaller and not always significant. At this depth, the soil of SF treatment did not differ significantly from the control. The soil of all the biochar treatments had slightly higher pH_{H2O} values than the soil of the control or SF treatments, but the difference was significant only in SB10 and SB20 ones, where no fertiliser had been applied. The differences between the biochar treatments were also insignificant.



Note. Explanation under Figure 1; the results with the same letter were not significantly different at $p < 0.05$.

Figure 7. Soil acidity (pH_{H2O}) values in upper (8-cm) (A) and lower (4-cm) (B) layers

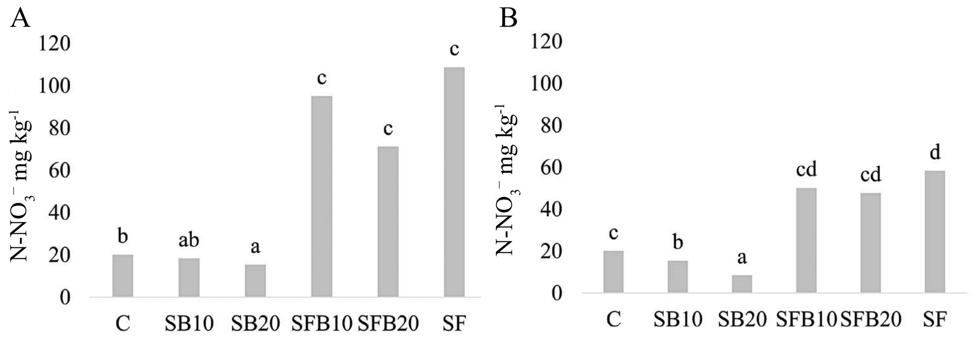
Application of the biochar to the unfertilised soil did not result in any significant change in the $N-NH_4^+$ amount: after the experiment, the soil in both the upper 8-cm and lower 4-cm layers had very low (6–8 mg kg^{-1} soil) amount of $N-NH_4^+$, and the differences between the treatments were not significant. Significant enrichment of the soil with $N-NH_4^+$ in both layers was found in all the fertilised treatments compared to the unfertilised ones. Despite the fact that the $N-NH_4^+$ amount in the soil of SF treatment was 30–40% lower than that in SFB10 and SFB20 treatments, the differences between the values were not significant. The amount of $N-NH_4^+$ in both soil layers were about the same independent of the fact that biochar and fertiliser were applied only in the upper 8-cm layer (Figure 8).



Note. Explanation under Figure 1; the results with the same letter were not significantly different at $p < 0.05$.

Figure 8. Available nitrogen ($N-NH_4^+$) content in the upper (8-cm) (A) and lower (4-cm) (B) soil layers

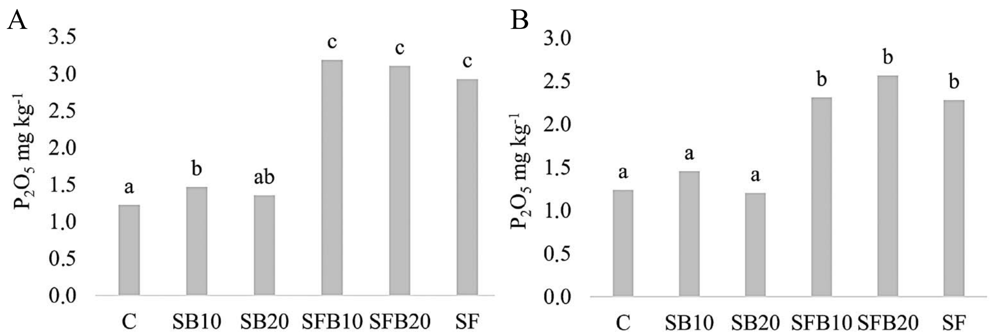
Application of biochar to the soil without fertiliser resulted in lower amount of $N\text{-}NO_3^-$ not only in the upper 8-cm layer, where the biochar had been applied, but also in the lower 4-cm layer. The reduction was significant for SB20 treatment in the topsoil and for both SB10 and SB20 ones in the lower layer. The fertiliser applied to the soil did not contain any available nitrogen in $N\text{-}NO_3^-$ form, but the soil after the experiment contained significantly higher amount of $N\text{-}NO_3^-$ both in the upper and lower layers under all the treatments with the fertiliser. The amount of $N\text{-}NO_3^-$ in the lower layer was almost twice lower than in the topsoil, but the difference between the soil layers was significant only at the SF treatment. Between the fertilised treatments, the higher amount of $N\text{-}NO_3^-$ was found in the soil of SF treatment compared to SFB10 and SFB20 ones, but the differences with the other fertilised treatments were insignificant (Figure 9).



Note. Explanation under Figure 1; the results with the same letter were not significantly different at $p < 0.05$.

Figure 9. Available nitrogen ($N\text{-}NO_3^-$) content in upper (8-cm) (A) and lower (4-cm) (B) soil layers

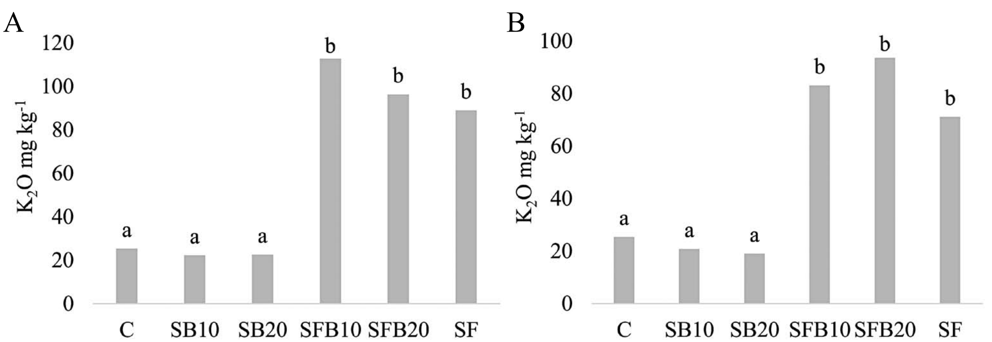
The content of P_2O_5 in the soil was very low, and the fertiliser application resulted in a significant increase in P_2O_5 content both in the upper and lower layers. In the soil of the fertilised treatments, P_2O_5 content was significantly higher in the upper 8-cm layer compared to the lower 4-cm one. Biochar application resulted in a slight increase in the content of P_2O_5 in both soil layers with all the biochar treatments, but the difference was significant only in the upper 8-cm layer for SB10 treatment (Figure 10).



Note. Explanation under Figure 1; the results with the same letter were not significantly different at $p < 0.05$.

Figure 10. Available phosphorus (P_2O_5) content in upper (8-cm) (A) and lower (4-cm) (B) soil layers

The content of K_2O in the soil without fertiliser was 19–25 mg kg^{-1}. Biochar application to the soil without the fertiliser did not result in any significant change in K_2O content both in the upper and lower layers, and the difference between the layers was not significant either. The fertiliser application led to a significant increase in K_2O content in both layers. Biochar application to the fertilised soil led to a slight increase in K_2O content in both layers, but the increase was not significant (Figure 11).



Note. Explanation under Figure 1; the results with the same letter were not significantly different at $p < 0.05$.

Figure 11. Available potassium (K_2O) content in upper (8-cm) (A) and lower (4-cm) (B) soil layers

Discussion

Soil acidity (pH). Mineral fertiliser application to soils can result in soil and soil solution acidification and that, in due course, can lead to a whole series of unfavourable changes in the properties of arable soils. Historically, the most common management practice used to combat soil acidity is liming. Liming improves physical, chemical and biological properties of agricultural soils through its effects in ameliorating soil acidity, mobilizing plant nutrients, immobilizing toxic heavy metals and improving soil physical conditions (Blake, 2005). The results of our short-term experiment have shown that biochar could reduce acidity of the leachate and, also, the soil acidity not only in the layer, where the biochar had been applied, but also in the lower soil layer, where the biochar-affected water from the topsoil was moving to. In our experiment, the increase in the leachate pH under biochar effect was significant only at the higher (20 t ha^{-1}) biochar rate (SB20) both in the unfertilised and fertilised soils. Avoiding low soil leachate pH after fertiliser application can help with stabilizing basic cations, which are easily removable from the upper soil layers by acid soil waters in North-Western region of Russia. The more pronounced effect of higher biochar application rates on soil pH is in line with the results of many other studies (Hailegnaw et al., 2019; Mukhina et al., 2019).

Available nitrogen (N-NH_4^+ and N-NO_3^-) content. Mineral nitrogen in ammonium form was applied to the soil with the mineral fertiliser, and that must have been the main reason for significant increase in the concentration of N-NH_4^+ in the leachate from the fertilised soil compared to the unfertilised one. Application of the higher rate of biochar to the fertilised soil resulted in more even removal of N-NH_4^+ from the soil, but had no significant effect on the total amount of N-NH_4^+ leached from the soil during the experimental period. Ding et al. (2010) were also looking at biochar (made of bamboo) effect on nitrogen retention and leaching in a column experiment. They have shown that addition of biochar to the surface soil layer of a fertilised soil reduced the downward transport of N-NH_4^+ from this layer during the first 7 days of the experiment compared to the soil with fertiliser but without biochar. Later in the experiment (days 7–28), the N-NH_4^+ concentration in the leachate from the fertiliser + biochar treatment was significantly increasing compared to the fertiliser only treatments. When the same authors were analysing cumulative losses of ammonium ion from the soil, they found that the differences between the fertilised treatments with and without biochar were significant only at the beginning of the experiment. This is very similar to our findings.

N-NH_4^+ is being retarded from leaching by biochar for some time due to physical adsorption of ammonium ion within biochar micropores or by the mechanisms involved in the liming effect and increased nutrient holding capacity by biochar addition (Nguyen et al., 2020). Clough and Condron (2010) also explained adsorption of ammonia and increasing NH_4^+ storage by enhanced cation exchange capacity in soils. In our experiment, there was also a tendency in N-NH_4^+ accumulation in the upper and lower soil layers. Overall, the results suggest that N-NH_4^+ can be retained in the soil layer through biochar application for a short period of time, but even a short delay in N-NH_4^+ leaching is potentially beneficial to nitrogen utilization of crops.

Leaching of N-NO_3^- on the 1st day of the experiment was the same from the soil of all the experimental treatments indicating the same N-NO_3^- accumulation in the soil during the 5-day stabilization period and the same soil permeability independent of the fertiliser or biochar application. Some experiments have shown that biochar potentially has the ability to manipulate the rates of nitrogen cycling in soil systems by influencing nitrification rates (Clough, Condron, 2010), but it was also shown that this ability of biochar depends on the degree of biochar weathering (Clough et al., 2010). It was shown earlier that the reduction in N-NO_3^- leaching under the effect of biochar was significantly dependent on soil texture (Ghorbani et al., 2019) and affected by such soil physical property as hydraulic conductivity (Li et al., 2018): the more permeable was the soil the higher concentration of N-NO_3^- was found in the leachate. If the rate of biochar was high enough to alter the soil permeability, the loss of nitrate ions was also changing.

In our experiment, the soil was of sandy loam texture, which is usually characterized by high water permeability, and this probably was the main reason, why biochar did not have any effect on N-NO_3^- removal from the soil with the leachate. Though in the article of Borchard et al. (2019) based on the meta-analysis of data from 88 peer-reviewed publications, a 13% reduction in N-NO_3^- leaching was shown under biochar application. In the same paper, it was also shown that the reduction in N-NO_3^- leaching was dependent on time: the longer was the experiment, the better was the biochar effect. No effect of woody biochar on N-NO_3^- content in the soil was also reported by other researchers (Biederman, Harpole, 2013; Nguyen et al., 2020). In general, our results suggest that biochar does not help in preventing N-NO_3^- leaching from light-textured soils during the short-term period fallowing fertiliser application in the case of heavy precipitation.

Up to date, several mechanisms of nitrogen retention by biochar in soils have been proposed. These include adsorption of ammonia or organic nitrogen by biochar, reactions of cation or anion exchange, enhanced immobilization of nitrogen due to the addition of labile carbon with biochar (Clough et al., 2013). Studies of Yao et al. (2012) have clarified the potential role of biochar in relation to N-NO_3^- adsorption: they have analysed 13 types of biochar from different materials that were slowly pyrolyzed at 300, 450 or 600 °C temperature to determine their potential for removal of N-NO_3^- from solutions. As a result, it was determined that in order for biochar to have any potential for N-NO_3^- adsorption the pyrolysis process must occur at a temperature of at least 600°C. Kameyama et al. (2012) have found that the application of biochar to the soil could potentially increase the hydraulic conductivity or preferential flow of larger particles and thus lead to increased N-NO_3^- leaching. On the other hand, the same authors have shown that the introduction of biochar into the soil increased the soil water-holding capacity, which could reduce leaching of N-NO_3^-. Ultimately, the authors concluded that N-NO_3^- is only weakly adsorbed on biochar. It can be desorbed by infiltration water, but, as a result, the residence time of N-NO_3^- in the soil can increase. In turn, this may provide better possibility for plants and microorganisms to absorb this form of nitrogen.

Available potassium (K_2O) content. Up to date, there are controversial data on K_2O leaching from soils under the effect of biochar application. Nguyen et al. (2020) conducted a column leaching experiment, where it was found that biochar addition linearly and significantly increased K_2O concentration in the leachate on the sandy soil, while on the clayey one biochar addition showed no obvious effect on the leaching of this element compared to the non-biochar-added soil. The authors explained the effect by the fact of application of additional potassium with the biochar. Kuo et al. (2020) in the 42-day column leaching experiment with a sandy loam soil mixed with two types of biochar found that one of them was significantly reducing K_2O leaching from the soil, while the other made at higher pyrolysis temperatures was not. In this experiment, the biochar was made of saw dust and did not contain high content of extra K_2O.

According to our data, biochar application had a significant effect on K_2O concentration in the leachate from the studied soil of North-Western Russia both in the unfertilised and fertilised treatments. Leaching of K_2O from the fertilised soil was very similar to that of N-NH_4^+: application of the higher rate of biochar resulted in more even removal of K_2O from the soil, but unlike with N-NH_4^+ it also significantly reduced the total amount of K_2O leached from the soil. Reduction of K_2O concentration in the leachate was also found in the unfertilised soil on the 1st day of the experiment. Here K_2O removal from the soil was also more even during the three days compared to the other unfertilised treatments, and the difference in the total amount of K_2O leached from the soil was significant. The reason for K_2O concentration reduction in the leachate, and its slight but insignificant accumulation in both soil layers could also be related to the higher cation exchange capacity of the soil with biochar or to physical adsorption of potassium ions within biochar micropores (Wong et al., 2019). The increase in soil K_2O content was also shown in Gao et al. (2017). Results of our experiment suggest that K_2O as well as N-NH_4^+ can be retained in the soil through biochar application for a short period of time. In the two-year experiment, Zhang et al. (2020) have shown that by adding 2% of biochar to a soil it was possible to replace 40% of conventional K_2O fertiliser.

Available phosphorus (P_2O_5) content. Behaviour of P_2O_5 under application of biochar was also different in various experiments conducted up to date, but comprehensive and systematic understanding of the biochar-induced environmental behaviour of soil P_2O_5 has not been obtained so far. Nguyen et al. (2020) have found that biochar addition significantly increased P_2O_5 concentration in the leachate from a sandy soil but not from a clayey soil, where there was no obvious effect of biochar on the leaching of P_2O_5 compared to the non-biochar-added soil. Kuo et al. (2020) in a column leaching experiment with sandy loam soil have found that low-temperature biochar had no effect on P_2O_5 leaching, while high temperature biochar reduced P_2O_5 leaching significantly. Gao et al. (2017) have found that soil P_2O_5 content was increasing in the soil with the biochar application. Later Gao et al. (2019) through meta-analysis have shown that biochar generally enhances soil phosphorus availability when added to soils alone or in combination with fertiliser.

In our experiment, the initial P_2O_5 content in the soil was very low, and it was very unlikely that P_2O_5 concentration in the leachate from the fertiliser-untreated soil or in the soil would increase only due to biochar application. Biochar application at higher rate in combination with the mineral fertiliser (SFB20 treatment) was significantly reducing P_2O_5 leaching from the studied soil compared to the treatment with fertilisers only. Presumably high P_2O_5 adsorption capacity of biochars that was described in several articles (Antunes et al., 2017; Dai et al., 2020) was the main mechanism of mineral phosphorus retention in the studied soil. These results are in line with those of the studies (Zhou et al., 2018; Huang et al., 2020), where high rates of high-temperature biochar were used on light-textured soils containing significant amount of P_2O_5.

In their study, Prasad et al. (2020) highlighted that total amount of Ca and Mg in biochars could affect the availability of other nutrients including phosphorus for plants. They have also shown that total amount of Ca and Mg in biochars correlated with the biochars' pH values: the higher was the pH value, the higher was the total amount of Ca and Mg. The biochar studied in our experiment had relatively low pH, so it was unlikely that the biochar could contain total amount of Ca and Mg high enough to alter P_2O_5 content in the studied soil. In the literature review, Yang et al. (2021) have explored different ways of biochar effect on soil P abundance, availability and leaching, and they suggested that the application of biochar to soils can help enlarge soil P_2O_5 pools, increase P_2O_5 availability and decrease P_2O_5 leaching losses from soil. Results of our short-term experiment are in line with these suggestions, even if the increase in the soil P_2O_5 in the upper and lower soil layers was not significant for our short-term experiment.

Conclusions

The results of the short-term laboratory experiment showed that:

(1) the effect of biochar on the movement and accumulation of the main nutrients in the sandy loam soil after fertiliser application and under the effect of heavy precipitation was more pronounced at the higher biochar application rate of 20 t ha^{-1};

(2) due to alcoline nature, biochar application reduced the acidity of the leachate and, also, the soil acidity not only in the layer, where the biochar had been applied, but also in the lower layer affected by the leached waters;

(3) available nitrogen in N-NH_4^+ form, available potassium (K_2O) and available phosphorus (P_2O_5) were retained in the soil through biochar application for a short period of time presumably due to increased nutrient holding capacity of the soil by biochar addition;

(4) biochar does not help in preventing N-NO_3^- leaching from the sandy loam soil during the short-term period fallowing fertiliser application;

(5) overall, biochar can be used as an ameliorant of the arable sandy loam soil of North-Western Russia, as even a short delay in the nutrient leaching is potentially beneficial to nutrient utilization of crops.

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Gausių kritulių trumpalaikis poveikis maisto medžiagų išplovimui iš ariamojo smėlingo priemolio patręšus ir panaudojus bioanglį

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Santrauka

Tyrimo tikslas – įvertinti bioanglies panaudojimo įtaką pagrindinių maisto medžiagų išplovimui iš Rusijos Šiaurės Vakarų ariamojo smėlingo priemolio (*Albic Luvisol*) viršutinio sluoksnio po tręšimo mineralinėmis trąšomis esant gausiems krituliams. Vykdant trumpalaikį laboratorinį eksperimentą buvo tirti 6 variantai: (1) dirvožemis be trąšų ir bioanglies (kontrolinis variantas), (2–3) dirvožemis + bioanglis (10 ir 20 t ha^{-1}), (4) dirvožemis + trąšos ir (5–6) dirvožemis + bioanglis (10 ir 20 t ha^{-1}) + trąšos. Eksperimento metu dirvožemis cilindruose tris kartus buvo laistomas distiliuoto vandens didelėmis normomis (345 cm^3), atitinkančiomis didžiausią paros kritulių kiekį (44 mm), stebimą natūraliomis vietovės sąlygomis. Filtratas buvo surinktas 1-ą, 2-ą ir 5-ą eksperimento dieną; taikant pH_{H2O} metodą, nustatyti įsisavinamo azoto (N-NO_3^-, N-NH_4^+), fosforo (P_2O_5) ir kalio (K_2O) kiekiai. Eksperimento pabaigoje cilindruose buvo suformuoti atskiri mėginiai iš dirvožemio viršutinio (8 cm) ir apatinio (4 cm) sluoksnių ir nustatytos pH_{H2O} vertės ir N-NO_3^-, N-NH_4^+, P_2O_5 bei K_2O koncentracijos. Eksperimento rezultatai parodė, kad bioanglies įtaka pagrindinių maisto medžiagų judėjimui ir kaupimuisi dirvožemyje po tręšimo ir esant gausiems krituliams buvo didesnė panaudojus didesnę 20 t ha^{-1} normą bioanglies. Bioanglies įterpimas filtrato ir dirvožemio rūgštumą sumažino ne tik tame sluoksnyje, kuriame ji buvo įterpta, bet ir apatiniame, kurį paveikė filtratas. Panaudojus bioanglį, dirvožemyje trumpą laiką išsilaikė įsisavinamų N-NH_4+, P_2O_5 ir K_2O koncentracijos, o N-NO_3^- išplovimui bioanglis neturėjo įtakos.
Bioanglis gali būti panaudota kaip dirvožemį gerinanti priemonė, nes net trumpalaikis maisto medžiagų išplovimo sulaikymas augalams gali padėti įsisavinti maisto medžiagas.

Reikšminiai žodžiai: bioanglis, dirvožemis, filtratas, krituliai, maisto medžiagos, mineralinės trąšos.