Effects of biochar and fertilizer amendments on soil acidity and soil organic carbon content on Luvic Anthrosols in Russian Far East

Olga Nesterova[1], *Viktoriia* Semal[1,2*], *Maria* Bovsun[1,3], *Anastasia* Brikmans[1], *Nikolay* Sakara[4], and *Tatiana* Tarasova[4]

[1]FEFU, Far Eastern Climate Smart Lab, 10 Ajax Bay, Russky Island, 690922 Vladivostok, Russia
[2]Federal Scientific Center of the East Asia Terrestrial Biodiversity, Far Eastern Branch of the Russian Academy of Sciences, Prospekt Stoletiya Vladivostoka Ave. 159, 690022 Vladivostok, Russia
[3]Il'ichev Pacific Oceanological Institute, Far Eastern Branch of the Russian Academy of Sciences, Baltiyskaya st. 43, 690041 Vladivostok, Russia
[4]Primorskaya Vegetable Experimental Station of the All-Russian Scientific Research Institute of Vegetables, Kubanskaya St 57/1, 692779 Artyom, Russia

Abstract. The paper presents the results of a study effect of biochar together with fertilizers on the acidic properties and organic content in Luvic Anthrosols in the South of the Russian Far East during two years field experiment. As a result of the study, it was proved that the combination of biochar with organic fertilizers contributes to the preservation of organic carbon in the soil at the end of the growing season, even 16 months after application both on the drainage site and without drainage. The most effective shift of acidity values towards neutral occurs 4 months after the introduction of biochar and combination with fertilizers for all experimental variants on a non-drainage site. After 16 months the acidity values almost return to the original values of the beginning of the growing season.

1 Introduction

It is known that an increase in the world's population leads to such world problems as poverty and hunger, the solution of these issues is reduced to another problem - a decrease in soil fertility. The preservation and improvement of the fertility In agricultural soils has always associated with the application of fertilizers, soil cultivation and crop rotation. But now the first problem in the world is climate change and agriculture makes a significant contribution to greenhouse gas emissions. Therefore, we need modern approaches to regulating soil fertility, and one of them is the application of biochar into the soil. The results of many studies have confirmed that biochar could be used as a soil additive to improve soil properties, crop productivity, or to increase the retention or absorption of different compounds [1-5]. However, in agronomy the practice of biochar application is still being examined, with new innovative solutions being developed. The complexity of the interactions between the plant, soil, and biochar can be high, and determines the agronomic effects obtained [6]. The study

* Corresponding author: semal.va@dvfu.ru

https://doi.org/10.1051/e3sconf/202337106013

examines the change in the properties of soil biochar obtained from *Betula alba* tree residues after its application in a field growing experiment for two growing periods in the areas with different water-air conditions (with and without drainage).

Based on the abovementioned statements, the specific objective of this study is to evaluate and discuss the impact of biochar applied in a field experiment in 2018, in combination with drainage and not drainage system and with mineral and organic fertilizers on soil chemical properties (pH, SOC), measured two years after the biochar application. We test the hypothesis whether a single biochar addition application may provide benefits to soil chemical properties, or whether repeated biochar applications are needed to provide the abovementioned benefits in the future.

2 Materials and Methods

2.1 Climate

The Primorsky region is characterized by a moderate monsoon climate. The climate of the experiment area is cold and temperate. According to Köppen and Geiger [7], this climate is classified as warm humid continental climate (Dwb). The summers are much precipitation than the winters. According to the amount of precipitation in the study area, the considered growing seasons from 2018 to 2019 are characterized as abnormally wet (Figure 1). The total amount of precipitation for the period from April to October 2019 was higher than the total annual average value for the same period (2017 - 2018) (732 mm) by 300 mm. The most abnormally wet month for the two growing seasons was August. According to the average monthly value of air temperature, both the growing season of 2018 and 2019 did not have significant differences compared to the average long-term values (Figure 1).

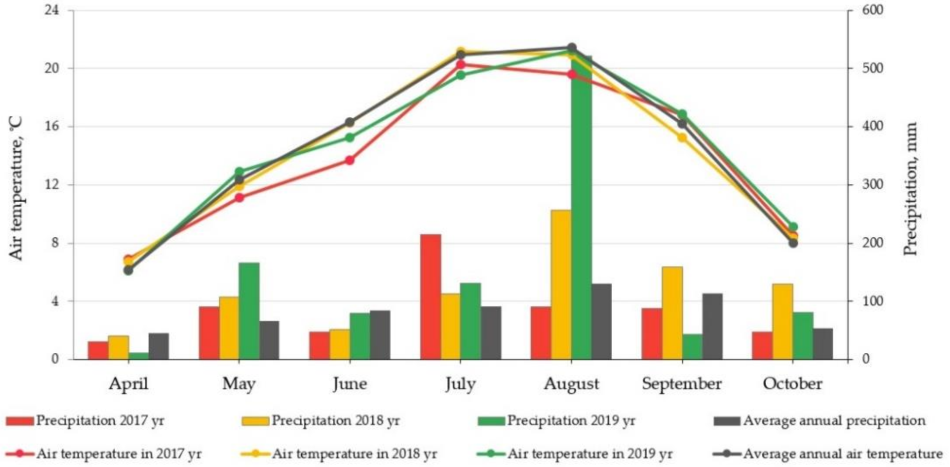

Fig. 1. Average air temperature and total precipitation during the growing seasons from 2017 to 2019 in the area of Primorsky Region (https://rp5.ru accessed on 4.08.2021).

2.2 Study Site and Description of the Field Experiment

The experimental plot of the Far East Federal University in Vladivostok is located on the territory of the Primorskaya Vegetable Experimental Station of the All-Russian Scientific Research Institute of vegetables (Surazhevka village, Primorsky Territory, Russian Federation, 43.423110, 132.313573). Field research was conducted on agricultural soil formerly under standard conventional practice and crop rotation. The experiment was established on Luvic Anthrosols (before plowing it was a loamy Haplic Luvisol). According to the World Reference Base of Soil Resources [8], the soil in the studied areas is represented by Luvic Anthrosols and has silty clay loam granulometric composition in plots without drainage system and silty loam granulometric composition in plots with drainage system (by classification FAO) at the beginning of experiment. Two adjacent fields were selected within the station, one of which has a drainage system (depth at 120 cm), the other does not. The initial characteristics of the topsoil at the study plot are presented in Table 1.

Table 1. Characteristics of topsoil (0-10 cm) Luvic Anthrosols before the experiment.

Soil Properties	**Values**	
	Field without drainage system	**Field with drainage system**
Sand, %	18	7
Silt, %	57	68
Clay, %	26	25
Bulk density (g cm-^{1})	1.2	1.2
Soil organic carbon (%)	2.6	2.1
pH (in 1 mol dm^{-3} KCl)	5.45	5.43
K_2O (mg kg^{-1})	200	104
P_2O_5 (mg kg^{-1})	140	90
N-eh (mg kg^{-1})	133	129

The main profile-forming process in Luvisols is lessivage (mechanical movement of silt down the soil profile without chemical change with the formation of a dense illuvial horizon Bt).

The organic carbon content are below the average, which are typical for Luvisols, which were present at experimental plot. The soluble potassium (K) content of the soil are average availability on a drainage system and high availability in a non-drainage system. The soluble phosphorus content is very low content on drainage system and high content in a non-drainage system.

The field experiment was set up in June 2018 before planting and included two treatments: without and with biochar soil amendment [9-10]. To study the biochar's effect on soil properties, the biochar was applied only once to soil at a rate of 10 and 30 t/ha. The biochar was spread on the soil surface and mixed with soil before planting. Nine plots were allocated on each field, a total of 18 plots. Each plot size was 21.6 m^2 (1.8 m × 12 m). Three plots of each field did not have biochar (control – BC0), the next three had 10 t/ha of biochar (BC1), and the following three contained 30 t/ha of biochar (BC3). At the same time, in each of the treatments with biochar, one area was allocated for the introduction of mineral fertilizers and organic fertilizers. As a mineral fertilizer, a complex diammophos fertilizer was used with a nitrogen content of 10%, phosphorus - 25% and potassium - 25%. Introduced 500 kg per 1 ha of soil. The organic fertilizer used was «Gigantin», a local organic fertilizer obtained from chicken manure at LLC «Ussuriiskaya Poultry Farm». It contains dry matter - 90%, nitrogen - 4.0%, phosphorus - 3.5%, potassium - 1.7%. The fertilizer application rate is 10 t/ha to the soil. The experiment diagram is shown in Figure 2.

Field without drainage system		
OBC0	OBC1	OBC3kg
MBC0	MBC1	MBC3
BC0	BC1	BC3

Field with drainage system		
DOBC0	DOBC1	DOBC3
DMBC0	DMBC1	DMBC3
DBC0	DBC1	DBC3

Fig. 2. Scheme of experiment. 0, 1, 3 – application doses of biochar (BC), kg/m^2. D – drainage; M - mineral fertilizers; O - organic fertilizers.

Soil samples from field with and without drainage system for laboratory were sampled randomly from the surface layer (0–10 cm) of each plot before planting and after the harvest in 2018 - 2019 and shipped to the laboratory and then the samples were air-dried. Each soil sample was taken in four iterations.

2.3 Biochar Making Process

The biochar used in this study was produced commercially by "Krasnilov and K°" company (Russia) from wood residues of *Betula alba* birch by slow pyrolysis at a temperature of 360 - 380^{0}C. Basic properties of biochar are presented in table 2. The biochar properties were evaluated according to the IBI International Standard [11]. The biochar used is an environmentally friendly, high-quality product with a strong, highly porous structure and good sorption properties [12]. Changes in the chemical and sorption properties of biochar after being in the soil for 1 and 2 years are described in detail in the work of Bovsun et al. [9].

Table 2. Basic properties of biochar from wood residues of birch *(Betula alba).*

Biochar Properties	Values
pH (H_2O)	8.9
Carbon (C), %	78
Nitrogen, %	0.08
Ash content, %	5.4 – 7.3
Volatile matter,%	29 – 31.2
H/C (molar ratio)	0.0518
O/C (molar ratio)	0.1452
EC, µS/cm,	186.3
Surface area, m^2/g.	73.25
Porosity, cm^3/g	0.048
H, %	4.04
O, %	11.34

2.4 Soil Sampling and Analysis

The soil samples were collected at vegetation intervals from the beginning (June) till the end (October) of the cabbage growing season in 2018 (from the 0 to 4st month since biochar application) and from June to October in 2019 during the vegetation season of potatoes in field with drainage system and soybean in field without drainage system (from the 12th to 16th month since biochar application). After removing the roots, the remaining bulk soil samples were dried at 105 °C.

https://doi.org/10.1051/e3sconf/202337106013

Standard soil analyses were used to determine the parameters, such as: soil pH was analyzed potentiometrically (FiveEasy Plus FP20, Mettler Toledo, Russia) in suspension with 1 mol dm^{-3} KCl solution ratio 1:2.5 [13]. Soil organic carbon (Corg) content was measured using the wet combustion method—oxidation of soil organic matter (SOM) by a mixture of 0.07 mol dm^{-3} H_2SO_4 and $K_2Cr_2O_7$ with titration using Mohr's salt [14].

3 Results and Discussion

3.1 Physical and Chemical Characteristics of the Soil

3.1.1 Soil acidity

The reaction of the soil solution is very important for the assimilation of nutrients by [15]. Most vegetable crops prefer the reaction of the soil solution closer to neutral, so it is necessary to select the optimal acidity values of soil solution for specific crops. It is known that biochar is able to influence changes in soil acidity and this is due to its effect on the water-air properties of soils and microbial activity [16]. When assessing the effect of only different doses of biochar on soils, we obtained the following data. The soil pH was significantly affected by the doses biochar, presence or absence of drainage, different types of tillage, and almost all the possible interactions between these factors. Soil pH(KCl) related to biochar and fields with and without drained system applied ranged from 5.5 (BCD0 in 2018 June) to 7.0 (BCD0 in 2019 June). After the application of biochar, already at the end of the vegetation season, the values slightly increase, which corresponds to the literature data [17]. But the next year, at the beginning of the vegetation season, the pH values fall even below the initial values before the application of biochar. Biochar has a better effect on the change in acidity in the field without drainage system, which corresponds to the state of natural soils in the study area. Among the doses of biochar, the dose of 10 t/ha proved to be the best; in this plot without drainage, the pH values increase during two growing seasons. Considering this, biochar may be a valuable tool in the management of agroecosystems and a plausible way to ameliorate acidic soils in particular, as suggested in a previous study by Horák [16]. As shown in figure 3 - 4, the soil pH values was increased in October 2018 (after four month after biochar application) in the field without drainage system during the first vegetation period, then they decline a little (except plot BC1). In field with drainage system the application of biochar decline pH values. At the end of the second vegetation season (16 months after biochar application) biochar increases pH values in field without drainage system, but in the field with drainage system, there is a slight increase in values (excluding the plot BCD1). Compared with the control, the changes in pH values between the biochar-amended treatment and the unamended control treatment indicated that there was increase in the first vegetation season in the field without drainage system, but the pH gradually declined at the second vegetation period in field with drainage system. The combined effect of biochar and organic and mineral fertilizers was also studied during the 2018-2019 vegetation season. At the beginning of the vegetation season in 2018, before the introduction of biochar, the acidity values in both the drainage and drainage-free control areas were in the range of 5.5 - 5.8. At the site with drainage system at the end of the vegetation season, at the control sites both with the introduction of organic and mineral fertilizers, and at the site without fertilizers, the acidity values vary from 6.8 -5.8. In the areas where biochar was introduced at doses of 10/ha and 30 t/ha, there is a shift in acidity in all variants of the experiment in the direction close to neutral and neutral from 6.0 – 7.2. In 2019, at the beginning of the growing season in the control plots, the acidity values in the control and with the use of mineral fertilizers were in the range of 5.5 - 5.9, and with the use of organic fertilizers, the acidity values were

7.1. In the areas where biochar was used, the acidity values ranged from 5.5 to 7.3, there was a noticeable shift in the neutral side of pH with the use of organic fertilizer. At the end of the growing season of 2019, the acidity values at the site in the control variants return to their original values (June 2018) towards a slightly acidic pH, and the introduced doses of biochar slow down this process.

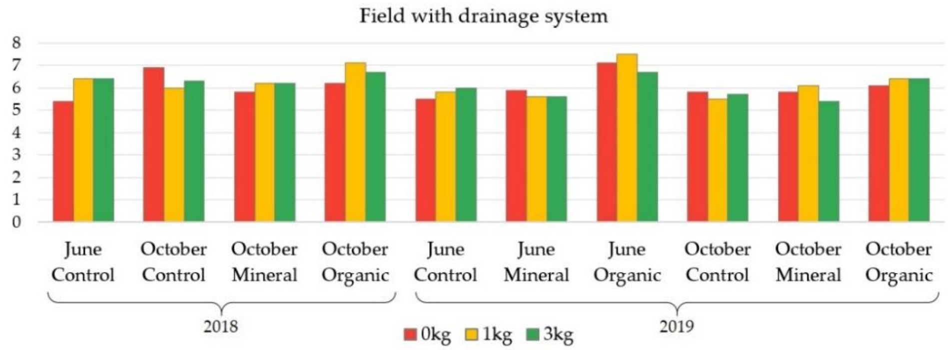

Fig. 3. The value of soil acidity pH_{KCl} with drainage system.

At the site without a drainage system at the end of the vegetation season of 2018, acidity values ranging from 5.8 – 6.5 are observed in control areas. In the areas where biochar was used, the acidity values shift towards a close to neutral from 6.0 - 6.9. At the beginning of the growing season of 2019, the acidity values in the control areas ranged from 6.1 - 6.4. In the areas with the introduction of biochar, the acidity values ranged from 5.5 - 6.5. The lowest value corresponds to a site with a dose of 30 t/ha of biochar without fertilizers, due to the high sorption capacity of biochar [9] and heavy granulometric composition of soils. At the end of the vegetation season of 2019, no significant changes between pH values were detected in all the studied areas. At the site with the application of organic fertilizer and bio-coal at a dose of 30 t/ ha, the pH is closer to neutral.

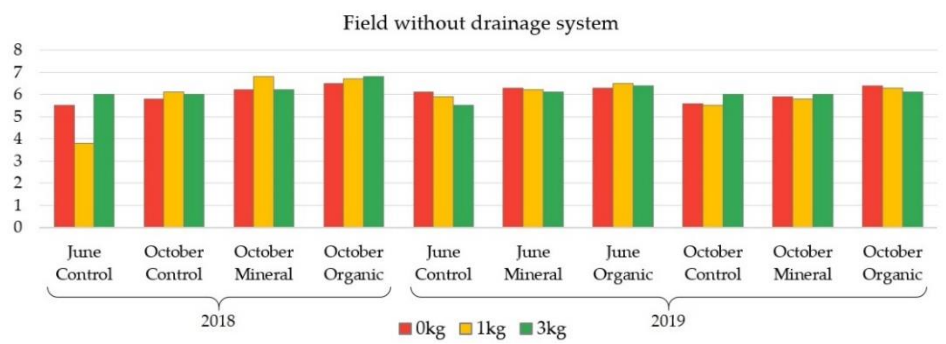

Fig. 4. The value of soil acidity pH_{KCl} without drainage system.

Biochar showed the greatest influence on the change in pH values towards neutral only in 2018 at the end of the growing season (4 months after application). After 16 months after its introduction, the effect on the acidity of the soil gradually decreases.

3.1.2 Soil total organic carbon content

Organic carbon is an important component in the soils, it is part of the humus of soils and determines the fertility of the soil. To increase soil fertility, various improvers are used, including biochaar and organic fertilizers. The evaluation of the impact of biochar alone showed that applications of biochar, alone and in combination with drainage system, had positive effects on soil organic carbon (SOC). Biochar is a stable form of carbon with resistance to microbial degradation [18], resulting in a SOC increase. The results showed that biochar application produced significant changes in Corg. These results are not surprising because biochar is a significant source of organic carbon (C) [18] and biochar used in this study contained 78% of total organic C. The most significant effect of applied biochar on increase of Corg was observed in treatment BC3 when compared to BC0 in the field without drainage system (0.6 units) and in treatment BCD1 when compared to BCD0 in the field with drainage system (0.5 units). Even though the average values of Corg increased after biochar application overall, its dynamics during the investigated periods were different during the vegetation period of 2018 – 2019. The dynamics of Corg revealed no trend in all biochar treatments with and without drainage and control (BC0), except BCD3 treatment. In BC3 the contents of Corg decreased with time during the vegetation seasons from 2018 to 2019. Biochar 16th month after application to the soil increased the content of Corg, but then gradually its content decreased, as shown by our results (figure 5-6). Biochar could be subjected to mineralization, resulting in a decrease of its volume in soil, including a decrease in soil Corg as a result of positive priming effect [19]. As reported in the literature, this is associated with biochar properties, particularly depending on the feedstock used and the production process itself [20]. Although biochar can improve degraded soils, it is not a one-size-fits-all solution. Soil and crop-specific biochar are needed in order to ensure optimum crop yield and agricultural sustainability. The combined effect of different doses of biochar and fertilizers showed that before the experiment, the organic carbon content in the control area without biochar and fertilizers was the lowest and was at about 2%. Fertilization increases this indicator and on the site with organic fertilizer, this value is slightly more than 3%. At the end of the vegetation season (4 months after the introduction of biochar), the highest carbon values correspond to the site with a dose of 30 t/ha of biochar in combination with organic fertilizers and amount to 4.4%, the convergence between the carbon determination rates is within ± 0.1 (Fig.5).

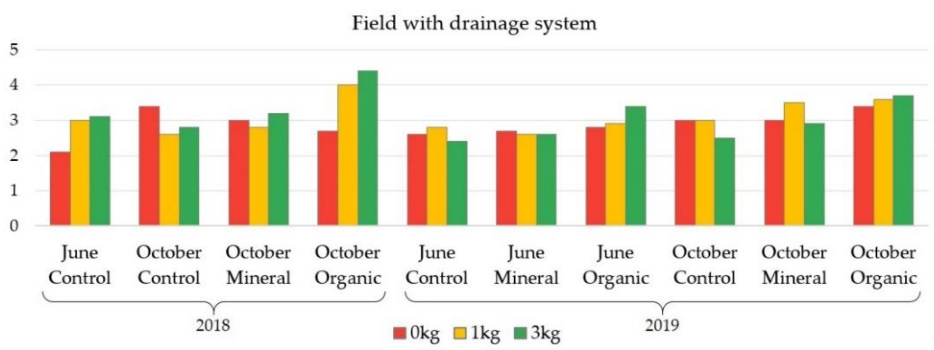

Fig. 5. Soil organic carbon content in field with the drainage system, %.

At the beginning of the 2019 vegetation season, the organic carbon content actually returned to the carbon values of the beginning of the 2018 vegetation season. 16 months after the introduction of biochar together with fertilizers, the maximum carbon values, as in 2018, are characteristic of the site where 30 t/ha doses of biochar and organic fertilizers were combined (Fig. 6). At the control without the biochar application, the value of organic carbon increases slightly (2.3%) by the end of the first vegetation season (2018) increases by 0.3 unit and remains unchanged for the second year by 2.6%. On plots with the use of mineral fertilizers at the beginning of the vegetation season, the value of Corg 1.6% and during the vegetation season increases by 0.6 unit. At the beginning of the second vegetation season, due to mineralization of organic residues, the value of Corg increases by 0.2 unit compared to the end of the first vegetation season. During the vegetation season of 2019, the value of Corg increases to 2.7%. In the control plots with the use of organic fertilizers during the first vegetation season, there was a decrease in the amount of organic matter by 0.5 unit compared to the beginning of the vegetation season (2.7%). By the beginning of the second vegetation season, there was an increase in the content from Corg to 2.9%, which was due to the introduction of organic fertilizers. By the end of the second vegetation season Corg increased slightly to 3.0%.

At the experimental plots with dose of biochar 10 t/ha at the beginning of the vegetation season of 2018, the value of the organic carbon was 2.3% and increased by 0.2% in the end of the vegetation season. During the second vegetation season, the values of Corg did not change (2.6%). On plots with the combined use of 10 t/ha of biochar and mineral fertilizers during the vegetation season of 2018, there was an increase of 0.9% from organic carbon compared to the beginning of the vegetation season (1.6%). By the beginning of the vegetation season of 2019, there was an increase in the organic carbon to 3.1% due to the mineralization of organic matter, similar to plots without biochar. By the end of the vegetation season of 2019, the number of organic carbon increased to 3.6%. On plots with the combined use of 10 t/ha of biochar and organic fertilizers during the first vegetation season, the value of organic carbon remained unchanged (2.7%), which may be due to the use of not only biochar, but also organic fertilizers. During the second vegetation season after the application of organic fertilizers, the values of organic carbon increased to 3.1% and by the end of the vegetation season decreased to 2.9%. On experimental plots with the use of 30 t/ha of biochar during the first vegetation season, there was a decrease in organic carbon by 0.2% compared to the beginning of the vegetation season (2.3%). By the beginning of the second vegetation season, an increase in the organic carbon value to 2.4% was noted. By the end of the second vegetation season, organic carbon increased by 0.2%. In plots with the combined use of 30 t/ha of biochar with mineral fertilizers, the organic carbon value increased by 0.9% by the end of the first vegetation season to 2.5%. At the beginning of the second vegetation season, due to the mineralization of organic matter, the value of organic carbon increased to 3.1%, and by the end of the second vegetation season, organic carbon decreased by 0.2% and amounted to 2.9%. In areas with the combined use of 30 t/ha of biochar with organic fertilizers during the first vegetation season, there was a slight increase of 0.1% to 2.8%. By the beginning of the second vegetation season, the value of organic carbon increased to 3.4% and decreased slightly to 3.3% by the end of the vegetation season.

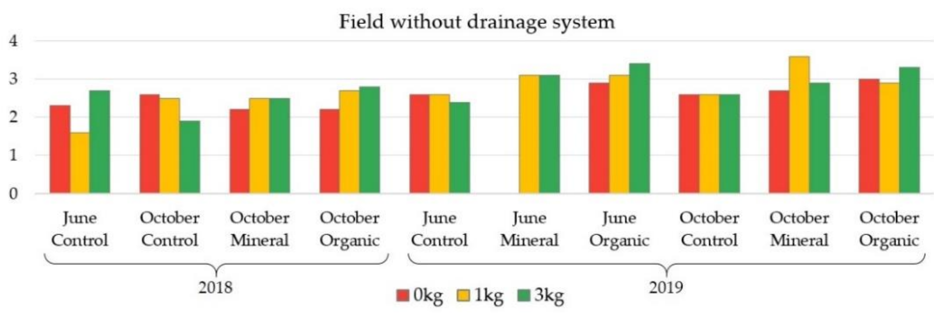

Fig. 6. Soil organic carbon content in field without the drainage system, %.

4 Conclusions

Thus, in summary, we can conclude that in recent years, the problem of environmental pollution has become increasingly serious with the increase in fertiliser consumption. As a soil amendment, biochar can retain and increase nutrients in soil. The reason is that the addition of biochar increased the soil acidity and increased organic carbon content due to its large specific surface area and high porosity [21]. Firstly, a proper amount of biochar significantly adjusts the soil properties – acidity and soil organic carbon. The effect of biochar on the pH shift towards neutral is insignificant due to the high content of silt particles. Through the application of biochar, the soil pH and soil organic carbon content both increased in field without drainage compared to a drainage system. Even though the properties of the soil were improved as a result of the application of biochar, the yield parameters and the overall grain yield depended significantly on the climatic conditions in the individual years [9]. Application biochar in Luvic Anthrosols in the climatic conditions of the south of the Russian Far East affected the soil characteristics leading to an increase in soil pH, an improvement in the amount of soil organic matter. Use of mineral fertilizers increases organic carbon regardless of the dose of biochar and leads to an increase in organic carbon values during two periods of vegetation compared to the control, with the exception of the plots with the use of 30 t/ha of biochar at the end of the second vegetation season. The combined use of both doses of biochar with organic fertilizers in the second vegetation season slightly lowers Corg. Secondly, adding a certain amount of biochar can significantly improve fertilizer use efficiency, which is conducive to improving yield. Finally, it is worth mentioning that biochar has the potential to reduce fertilizer inputs, and the potentiality depends on the amount of biochar applied. As future research, it seems promising to investigate the roles of more parameters of the soil properties and to explore the effect of biochar application on soil properties and further research should focus on the prolonged action of biochar combined with fertilizers in soil and changes in soil parameters and its relation to grown crops in biochar-amended soils during 3-4 years.

Acknowledgments

This work was supported by the Russian Foundation for Basic Research (grant № 19-29-05166/19).

References

1. D.L. Jones, J. Rousk, G. Edwards-Jones, T.H. DeLuca, D.V. Murphy, Soil Biol. Biochem. **45**, 113–124 (2012) https://doi.org/10.1016/j.soilbio.2011.10.012
2. T.J. Clough, L.M. Condon, C. Kammann C. Müller, Agronomy **3**, 275–293 (2013)
3. T. Riedel, P. Hennessy, S.C. Iden, A. Kochanski, Eur. J. Soil Sci. **66**, 823–834 (2015) https://doi.org/10.1111/ejss.12256
4. P. Bista, R. Ghimire, S. Machado, L. Pritchett, Agronomy **9**, 623 (2019) https://doi.org/10.3390/agronomy9100623
5. R. Baigorri, S. San Francisco, O. Urrutia, J.M. Garcia-Mina, Agronomy **10**, 968 (2020) https://doi.org/10.3390/agronomy10070968
6. A. Mukherjee, R. Lal, Soil Res. **52**, 217–230 (2014) https://doi.org/10.1071/SR13359
7. T.L. McKnight, D. Hess, *Climate Zones and Types: The Köppen System Physical Geography: A Landscape Appreciation* (NJ. USA, Prentice Hall: Hoboken, 2000)

8. *Guidelines for Soil Description* (Food and Agriculture Organization of the United Nations, Rome, Italy, 2006)
9. M.A. Bovsun, S. Castaldi, O.V. Nesterova, V.A. Semal, N.A. Sakara, A.V. Brikmans, A.I. Khokhlova, T.Y. Karpenko, Agronomy **11**, 1559 (2021) https://doi.org/10.3390/agronomy11081559
10. Y.A. Kolesnikova, V.A. Semal, O.V. Nesterova, S. Castaldi, M.A. Bovsun, A.V. Brikmans, A.D. Popova, E.A. Suvorova, Proceedings of the E3S Web of Conferences **175** (2020) https://doi.org/10.1051/e3sconf/202017509014
11. *Product Definition and Specification Standards: Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil (IBI Biochar Standards) Version 2.1* (IBI, 2015)
12. M.A. Bovsun, O.V. Nesterova, V.A. Semal, A.I. Khokhlova, N.A. Sakara, Proceedings of the E3S Web of Conferences **217**, 1-9 (2020) https://doi.org/10.1051/e3sconf/202021710009
13. L.P. van Reeuwijk, International Soil Reference and Information Center **9** (2020) ISSN 0923-3792
14. A. Walkley, J. Agric. Sci. **25**, 598–609 (1935) https://doi.org/10.1017/S0021859600019687
15. G.W. Thomas, *Soil pH and Soil Acidity. Methods of Soil Analysis. SSSA Book Series* (John Wiley & Sons. Ltd, 1996) doi:10.2136/sssabookser5.3.c16
16. J. Horák, Acta Hortic. Reg. **18**, 20–24 (2015)
17. M. Paneque, J.M. de la Rosa, A.F. Patti, H. Knicker, Changes in the Bio-Availability of Phosphorus in Pyrochars and Hydrochars Derived from Sewage Sludge after Their Amendment to Soils. Agronomy. 2021, 11, 623. https://doi.org/10.3390/agronomy11040623
18. D. Fischer, B. Glaser, Management of Organic Waste, IntechOpen, 167–198 (2012) https://doi.org/10.5772/31200
19. T. Whitman, B.P. Singh, A.R. Zimmerman, *Biochar for Environmental Management, Science, Technology and Implementation* (Taylor and Francis Group, London, UK; New York, NY, USA, 2015)
20. B.P. Singh, A.L. Cowie, Sci. Rep. **4**, 1–9 (2014) https://doi.org/10.1038/srep03687
21. J.M. Novak, W.J. Busscher, J.E. Amonette, J.A. Ippolito, I.M. Lima, J. Gaskin, K.C. Das, C. Steiner, M. Ahmedna, Soil Sci. **177**, 310–20 (2012) http://dx.doi.org/10.1097/SS.0b013e31824e5593