Pol. J. Environ. Stud. Vol. 29, No. 5 (2020), 2995-3001
DOI: *10.15244/pjoes/113128* ONLINE PUBLICATION DATE: 2020-03-16

Review

Biochar: An Important Component Ameliorating the Productivity of Intensively Used Soils

Ján Horák[1]*, Vladimír Šimanský[2], Dušan Igaz[1], Martin Juriga[2], Elena Aydin[1], Martin Lukac[3]

[1]Department of Biometeorology and Hydrology, Slovak University of Agriculture, Nitra, Slovakia
[2]Department of Soil Science, Slovak University of Agriculture, Nitra, Slovakia
[3]School of Agriculture, Policy and Development, University of Reading, Reading, UK

Received: 8 July 2019
Accepted: 16 October 2019

Abstract

Recently, biochar has been the focus of increasing research attention. Reflecting this trend, a field experiment was set up to test the potential of biochar as a soil ameliorant in Slovakia in 2014. This is a collaborative effort, where local core teams from the Slovak University of Agriculture and the Slovak Academy of Sciences work together with international experts to elucidate the effects of biochar addition (Poland, Russia, Switzerland, Czech Republic and the UK). Since the start of the experiment, a number of interesting findings have been made and widely published. Both positive and negative impacts of biochar application on soil function and its ability to support crop production were found. Reduction of greenhouse gas (CO_2, N_2O) emissions from the soil into the atmosphere after biochar application was among the key foci of the experiment. In the future, research broadening the knowledge base on biochar use should focus on: (i) economically cost-effective biochar production and application within the Slovak Republic to different soil types, (ii) the nutrient content of biochar, both total content and available forms and their ratio, with the view of eliminating negative impacts of biochar on crop yields; (iii) different types of biochar and their combinations with other organic and/or mineral fertilizers and their repeated application, (iv) optimum biochar application rates to improve the sustainability of agricultural production.

Keywords: biochar, soil properties, greenhouse gas emissions, crop yields, sustainable agriculture

Introduction

One of the reasons for the lack of progress in increasing food production to feed a growing human population is continuous degradation of soil resources in the 21st century. The production function of arable soils thus clearly plays a critical role in the future of humankind [1]. The concept of soil quality, an important but elusive concept still waiting for a clear definition, is a useful indicator of the capacity of the soil to support crop growth and thus food production. Soil quality has received substantial attention in scientific literature and is often used as a diagnostic tool for monitoring and to inform management of agricultural soils. Agricultural land in 2016 covered about 4.9 billion ha worldwide, corresponding to 37.6% of the total world land area

*e-mail: jan.horak@uniag.sk

[2]. Overall, about 1.035 mil ha of world soils is degraded due to anthropogenic impacts [3]: industry, urbanization, deforestation, agriculture and overgrazing contribute 1%, 7%, 30%, 28% and 34% of total soil degradation by human activity, respectively.

Agriculture, as one of the chief drivers of land use change and deforestation, has clearly had a major impact on terrestrial biosphere. Continuing with past trends may fundamentally threaten and possibly jeopardize the future of food production. The human population has grown 10 times over the past 300 years to reach 7 billion, and UN estimates indicate that it could reach 9 billion by 2050 [4]. Globally, there was 0.5 ha of arable land per capita in 1950, now we have to make do with 0.2 ha, and this area is further predicted to decrease to only 0.14 ha and even 0.1 ha in 2050 and 2100, respectively [5]. Currently, 6.350 m^2 of soil is lost globally every second, the two trends of arable land loss and human population rise conspire to create a significant challenge for agriculture. For example, annual loss of agricultural land is estimated to be 430 km^2 in Germany, 130 km^2 in the Netherlands, 120 km^2 in Austria, 30 km^2 in Switzerland and between 30 to 50 km^2 in Slovakia [6]. Conversion of land to agriculture appears to have run its course in the 'developed' world – in fact the area of agricultural land is decreasing, but 'developing' countries are still characterized by a relatively high rate of land use change to agriculture [7]. Forecasts by the FAO [2] confirm that land-based food will remain the main source of nutrition for the human population on Earth in the third millennium. To reach effective and sustainable soil management, we need to set up correct priorities in evaluating soil properties, understand the causes of decreasing or low soil fertility and establish the strategies for soil fertility improvements. In the future, a movement toward sustainable use of agricultural soils is an approach that should allow for the stabilization and potential increase in fertility and productive capacity of soils. Alongside developing new technologies, such as precision agriculture, GMO crops, robotics, etc., an inspiration can also be found in the application of traditional methods of soil fertility improvement to modern agriculture. History shows a number of useful examples where people attempted to improve soil properties by the application of charred wood [8-11]. The best-known example from scientific literature is the creation of the anthropogenic Chernozems, also called *Terra Preta de Índio*, by the Amazon Indians more than 8000 years ago [12]. These soils resulted from a substantial accumulation of organic waste materials such as kitchen leftovers, excrement and waste biomass, along with the remains of non-burned wood. These were further decomposed [13] and resulted in soils with surprisingly high fertility. The *Terra Preta de Índio* phenomenon has become the main inspiration of many scientists during the last two decades or so, with the main focus of their research on the role of biochar in the amelioration of soil properties and the question of whether the effect observed in Amazonia can be replicated in other areas of the world. A number of studies have shown that biochar as a soil additive has the potential to mitigate climate change by increasing soil organic carbon content and improving soil quality [14, 15]. Numerous studies representing a diverse range of soil-climatic conditions have indicated a positive effect of biochar on soil chemistry [16] and its capacity for nutrient supply to crops [17-20], improving biological soil properties [21] and physical soil properties [22-24]. It has also been shown that biochar increases crop yields [22, 25, 26], reduces greenhouse gas emissions (GHGs) and increases carbon storage in soils [27]. However, negative and no effects on soil characteristics and crop yields were also recorded [28], highlighting the need for further studies looking at the effects of biochar in a diversity of soil types and cropping systems.

Description of the Biochar Experiment in Slovakia

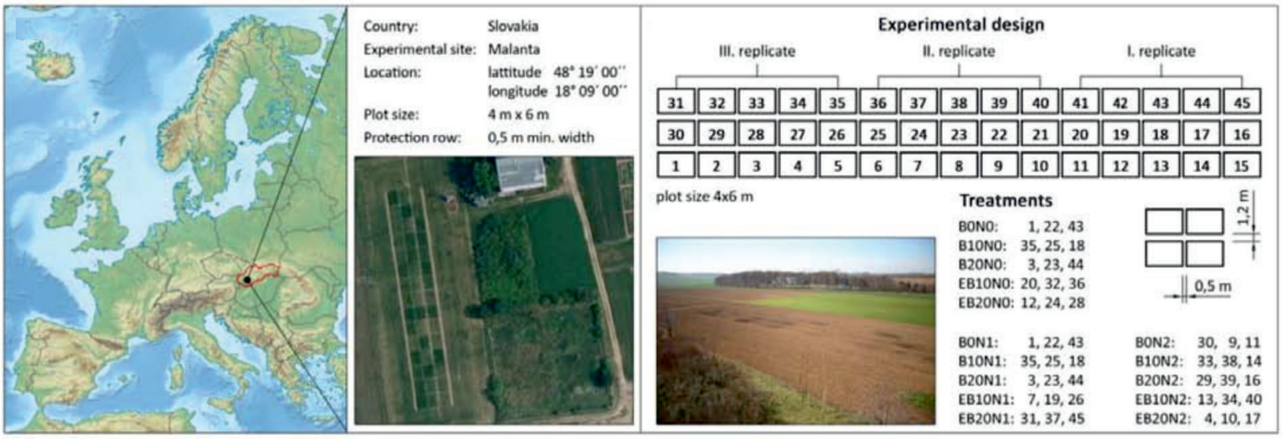
In Slovakia, little research looking into the effects of biochar on crop production and soil functioning was taking place before the early 2000s. In 2012, a research team was set up at the Slovak University of Agriculture in Nitra (SUA) with the aim of elucidating the potential of biochar as an ameliorant being able to improve the sustainability and productivity of agriculture. Over time, collaboration with other domestic institutions (Slovak Academy of Sciences – SAS) and foreign institutions such as the Warsaw University of Life Sciences (Poland), Nicolaus Copernicus University (Poland), Agrophysical Research Institute (Russia), Agroscope (Switzerland), University of Reading (United Kingdom), and the Czech University of Life Sciences (Czech Republic) has developed and increased the scientific effort devoted to this project. In 2014, a field experiment was established at the research base of SUA (in locality Malanta near Nitra city, Slovakia). The local soil type, Haplic Luvisol, represents about 11% (265.4 thousand ha) of total agricultural land in Slovakia [6], and approx. 500-600 mil. ha [29], worldwide. This experiment thus stands a reasonable chance of generating outputs with wide applicability to agricultural practice. The detailed description of the SUA experimental site (soil-climatic conditions) can be found in the scientific monograph by Tobiašová and Šimanský [30]. The structure and design of the experiment is shown in Fig. 1. Reduced soil cultivation practices were applied during the entire duration of the experiment. The area was sown with spring barley in 2014, corn in 2015, spring wheat in 2016, corn in 2017 and finally spring barley in 2018.

Published Outputs from the Biochar Experiment in Slovakia

A range of findings from this experiment, some of which are of interim nature as the experiment is still ongoing, has been published in domestic and international scientific journals and presented at domestic and international scientific events. Our results to date clearly confirm the positive effect of biochar application on soil organic content (SOC) shortly after application [31-34], which was still detectable 3 years into the experiment [35, 36]. The most beneficial effect on SOC was found after the application of 20 t ha^{-1} of biochar. The increase in SOC was also found in the soil of the plots where biochar was applied in combination with N fertilizer, but the nitrogen application rate was found to limit C accumulation in the soil [32, 33]. Significant differences in labile C content were observed in fractions of water-stable aggregates as a result of biochar application [36-38]. The highest biochar and fertilizer application rates significantly increased total C content in water-stable aggregates throughout the duration of the experiment [36, 38]. In addition to the standard soil organic matter parameters, the focus has also been on the calculation of C indexes that more precisely reflect changes in soil organic matter composition resulting from land management changes (e.g., after biochar application) [33]. Quantitative and qualitative indices describing humus content generally reflected the trends found in the C content of the soil. Concentration of humic substances and the intensity of the humification processes decreased significantly under higher biochar and fertilizer application rates [35].

Biochar is often shown to be an effective tool for greenhouse gas emissions mitigation from soils [39, 40]. In our experiment, we used not only the classic combination of biochar and fertilizer, but also biochar enriched with compost and mineral N (EBC, purchased

a) b)



Application	2014	2014	2015	2016	2017	2018
Treatment code	Biochar dose (t ha^{-1})	N fertilizer dose (kg ha^{-1})				
B0N0	0	0	0	0	0	0
B0N1	0	40	160	100	160	40
B0N2	0	80	240	150	240	80
B10N0	10	0	0	0	0	0
B20N0	20	0	0	0	0	0
B10N1	10	40	160	100	160	40
B20N2	20	80	240	150	240	80
Treatment code	Enriched biochar dose (t ha^{-1})	N fertilizer dose (kg ha^{-1})				
EB10 N0	10	0	0	0	0	0
EB20 N0	20	0	0	0	0	0
EB10N1	10	40	160	100	160	40
EB20N1	20	40	160	100	160	40
EB10N2	10	80	240	150	240	80
EB20N2	20	80	240	150	240	80

Fig. 1. Location of the site a) and a schematic layout of the experiment b).

as a ready-to-use product). Biochar was sprayed with 10% ammonium sulfate and when cold mixed with organic material for compost in the ratio of 50:50% v/v, and co-composted prior to application. The results showed that the application of biochar alone at two rates (10 and 20 t ha^{-1}) and in combination with the lower nitrogen rate (40 kg N ha^{-1}) significantly reduced CO_2 emissions from the soil. At the same time, the combination of the lower rate of biochar (10 t ha^{-1}) with the higher rate of N (80 kg N ha^{-1}) increased these emissions. Likewise, enriched biochar (EBC), whether applied alone or with N-fertilizer, significantly increased CO_2 production ($p < 0.01$). These results indicate that biochar not combined with compost and nitrogen appears to be an effective tool for reducing CO_2 flux into the atmosphere and for soil C retention. Conversely, the application of enriched biochar is not effective in terms of limiting CO_2 emissions as a significant greenhouse gas [41]. N_2O emissions were also measured in this field experiment to assess overall greenhouse gas emissions as affected by biochar application. Significantly lower N_2O emission peaks were recorded from soils with biochar application compared to those without biochar, resulting in lower cumulative N_2O emissions from biochar-amended soils during the first year of the experiment. Total cumulative N_2O emissions (taken between March and November 2014) from the soil with biochar with or without N-fertilizer were 19-32% lower than those from the soil without biochar [42]. The results confirm that biochar application has the potential to reduce N_2O emissions from the soil.

Soil organic matter is in close relation with soil structure, as the soil particles are often held together by organic binding substances. It was shown that biochar improved soil aggregation (clod formation) and structure stability (elimination of clod disintegration). The content of water-stable macro-aggregates has increased the most in the soil with 20 t ha^{-1} of biochar and the higher rate of N, which also resulted in higher aggregate stability and better ability of the soil to withstand crusting [32, 33, 36, 38]. Improved soil structure stability has contributed to the improvement of other physical and hydro-physical soil properties and resulted in decreased soil bulk density, increased soil water content and higher soil water retention capacity [34, 43, 44].

Biochar is a soil ameliorant that significantly increases pH value of acidic soils [45, 46]. Increased content of SOC as a result of biochar application is also likely to contribute to an improvement in the soil sorption indicators [34, 46, 47]. The soil sorption complex became fully saturated after biochar application, and it was shown that soil sorption is mainly affected by the biochar application rate (the higher the biochar rate, the higher the soil sorption) and the combination with N fertilization. A lower rate of N-fertilizer combined with a lower dose of biochar as well as a higher rate of N with a higher dose of biochar resulted in positive effects on sorption characteristics [48, 49]. The effect of biochar application on soil pH, as well as on the soil sorption capacity, in our experiment was the highest shortly after biochar application and has receded with the progress of the experiment. Total nutrient content of the soil (except for Ca) and their available forms (except K and Zn) have not been significantly altered by biochar application. A higher dose of biochar has resulted in a significant reduction in total and available Mn and Ni contents in the soil. For this reason, if biochar is to be applied to a soil where nutrient deficiency is an issue, attention must be paid to nutrient availability and its reaction to biochar application [48, 49].

One of the more interesting effects of biochar application to arable soils is that on crop production and yield. A positive effect of biochar application at the rate of 10 t ha^{-1} was observed on the amount of aboveground biomass, the number of ears, the number of grains, the number of ears per plant and the final yield of spring barley in the first year of experiment. Combining biochar with higher N fertilizer rate also had a positive effect on the evaluated crop parameters. On the other hand, the negative effect on the crop parameters was observed at the higher biochar rate, as well as at the combination of the lower biochar rate with the lower rate of N [50]. Likely, there is a strong interaction between a multitude of factors such as the exact combination of biochar with fertilizer, crop type, soil properties, application rate, time elapsed from biochar application, environmental conditions, etc., regulating the reaction of crop plants and their yields to soil amendment application. Factorial experiments are therefore one of the most effective ways of elucidating these relationships and interpreting in detail the impact of biochar on the particular crop. Early results from this experiment observed in 2014 could be indicative of a rapid change in soil properties, the highest barley yields were obtained in plots with pH of about 5.65 [42]. During the growing season a conventional digital camera was used as a non-destructive non-contact method of crop emergence monitoring and crop growth development [51]. Depending on the crop, photographs were taken above the canopy at various developmental stages – from the beginning of emergence to grain maturity. The vegetation index was then determined as a ratio of the green pixels (plant mass) representation to all pixels in the photograph [52]. Based on the vegetation indices evaluation, the combination of biochar with lower rate of N fertilizer appeared to be the most stimulating for early crop development. In 2015, biochar exerted a strong influence on the canopy development and light capture by the crop [53], subsequent years, however, saw a decreasing influence of ameliorant on the development of crop biomass during the growing season (spring wheat in 2016, maize in 2017; [54, 55]). In 2016 in particular, N fertilization had a slightly greater impact on biomass accumulation than biochar application. The green index method appears to be particularly suitable for crop emergence monitoring, rather than for the final crop biomass and yield prediction.

Conclusions

It is clear that the research activities in the realm of biochar application are progressing and starting to offer a good picture of mechanisms and effects. The findings from the field experiment in Malanta (Slovakia) are a valuable contribution to this dataset. Results of this experiment help to fill knowledge gaps in this area of biochar application to arable soils, the greatest contribution stems from the fact that the experiment is still ongoing. The findings confirm the fact that biochar produced by organic waste pyrolysis (not containing harmful and hazardous substances) contributes to soil fertility and supports sustainable soil management. Considering plant nutrition, it is important to pay increased attention to the application of other nutrients to soils where biochar has been added to satisfy nutrient requirements of individual crops. This requires more time to provide recommendation developed from longer-term observations of nutritional status in plants in relation to the release of nutrients from biochar into the soil.

One of the key unresolved issues inherent to biochar application is its economic viability – does the benefit of biochar to crop production outweigh the cost of its production? We show that the effects of biochar are limited and decrease in time, and future research should address its subsequent re-application to the soil in various combinations with fertilizers and application rates. Agricultural practice is actively looking for this type of information. Knowledge of optimum biochar application rates and its economic viability in different soil-climatic conditions becomes very important as farmers begin to understand the limits of intensive crop production. We believe that the outputs from this project will contribute to the knowledge base not only in Slovakia but will also be of global relevance.

Acknowledgements

This study was supported by the Slovak Research and Development Agency under contract No. APVV-15-0160, Scientific Grant Agency MŠVVaŠ SR (VEGA) project Nos. 1/0747/20 and 1/0064/19 and Cultural and Educational Grant Agency MŠVVaŠ SR (KEGA) project No: 019SPU-4/2020.

Conflict of Interest

The authors declare no conflict of interest.

References

1. LAL R. Soils and food sufficiency, a review. Agron. Sustain. Dev. **29** (1), 113, **2009**.
2. Environment Statistics. Available online: http://www.fao.org/economic/ess/environment/data/land-use/en/ (accessed on 08.04.2019).
3. HARRISON P., PEARCE F. Atlas of Population & Environment, University of California Press: Los Angeles, USA, 204, **2000**.
4. CRUTZEN P.J., STOERMER E.S. The "Anthropocene" 2000. Global Change Newsletter. **41**, 17, **2000**.
5. LAL R. Soil management in the developing countries. Soil Sci. **165** (1), 57, **2000**.
6. ŠIMANSKÝ V., POLLÁKOVÁ N., CHLPÍK J., KOLENČÍK M. Soil Science, SUA: Nitra, Slovakia, pp. 399, **2018** [In Slovak].
7. VILČEK J. Potentials and quality parameters of agricultural land in Slovakia. Geografický časopis (Geographical Journal). **63** (2), 133, **2011** [In Slovak].
8. SHEIL D., BASUKI I., GERMAN L., KUYPER T.W., LIMBERG G., PURI R.K., SELLATO B., VAN NOORDWIJ M., WOLLENBERG E. Do anthropogenic dark earths occur in the interior of Borneo? Some initial observations from East Kalimantan. Forests. **3** (2), 207, **2012.**
9. DOWNIE A.E., VAN ZWIETEN L., SMERNIK R.J., MORRIS S., MUNROE P.R. Terra Preta Australis: reassessing the carbon storage capacity of temperate soils. Agr. Ecosyst. Environ. **140** (1-2), 137, **2011**.
10. BLACKMORE A.C., MENTIS M.T., SCHOLES R.J. The origin and extent of nutrient-enriched patches within a nutrient-poor savanna in South Africa. J. Biogeogr. **17** (4-5), 463, **1990**.
11. OGAWA M., OKIMORI Y. Pioneering works in biochar research, Japan. Aust. J. Soil Res. **48** (7), 489, **2010**.
12. GLASER B. Prehistorically modified soils of central Amazonia: a model for sustainable agriculture in twenty-first century. Philos. T. Roy. Soc. B. **362** (1478), 187, **2007**.
13. GLASER B., BIRK J.J. State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (*terra preta de* Índio). Geochim. Cosmochim. Ac. **82**, 39, **2012**.
14. LAIRD D., FLEMING P., WANG B., HORTON R., KARLEN D. Biochar impact on nutrient leaching from a Midwestern agricultural soil. Geoderma. **158** (3-4), 436, **2010**.
15. ZHANG A., BIAN R., PAN G., CUI L., HUSSAIN Q., LI L., ZHENG J., ZHENG J., ZHANG X., HAN X., YU X. Effects of biochar amendments on soil quality, crop yield and greenhouse gas emission in a Chinese rice paddy: a field study of 2 consecutive rice growing cycles. Field Crop. Res.. **127**, 153, **2012**.
16. GONDEK K., MIERZWA-HERSZTEK M., KOPEĆ M., SIKORA J., GŁĄB T., SZCZUROWSKA K. Influence of biochar application on reduced acidification of sandy soil, increased cation exchange capacity, and the content of available forms of K, Mg, and P. Pol. J. Environ. Stud. **28** (1), 103, **2019**.
17. YAVARI S., MALAKAHMAD A., SAPARI N.B. Biochar efficiency in pesticides sorption as a function of production variables – a review. Environ. Sci. Pollut. R. **22** (18), 13824, **2015**.
18. MIA S., SINGH B., DIJKSTRA F.A. Aged biochar affects gross nitrogen mineralization and recovery: a 15N study in two contrasting soils. GCB Bioenergy. **9** (7), 1196, **2017**.

19. BEUSCH CH., CIERJACKS A., BOHM J., MERTENS M., BISCHOFF W.A., FILHO J.C.A., KAUPENJOHANN M. Biochar vs. clay: Comparison of their effects on nutrient retention of a tropical Arenosol. Geoderma. **337**, 524, **2019**.
20. EL-NAGGAR A., LEE S.S., RINKLEBE J., FAROOQ M., SONG H., SARMAH A.K., ZIMMERMAN A.R., AHMAD M., SHAHEEN S.M., OK Y.S. Biochar application to low fertility soils: A review of current status, and future prospects. Geoderma. **337**, 536, **2019**.
21. LEHMANN J., RILLIG M.C., THIES J., MASIELL C.A., HOCKADAY W.C., CROWLEY D. Biochar effects on soil biota, A review. Soil Biol. Biochem. **43** (9), 1812, **2011**.
22. BIEDERMAN L.A., HARPOLE W.S. Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. GCB Bioenergy. **5** (2), 202, **2013**.
23. AJAYI A.E., HORN R. Modification of chemical and hydrophysical properties of two texturally differentiated soils due to varying magnitudes of added biochar. Soil Till. Res. **164**, 34, **2016**.
24. IGALAVITHANA A.D., LEE S.E., LEE Y.H., TSANG D.C.W., RINKLEBE J., KWON E.E., OK Y.S. Heavy metal immobilization and microbial community abundance by vegetable waste and pine cone biochar of agricultural soils. Chemosphere. **174**, 593, **2017**.
25. XU G., ZHANG Y., SUN J., SHAO H. Negative interactive effects between biochar and phosphorus fertilization on phosphorus availability and plant yield in saline sodic soil. Sci. Total Environ. **568**, 910, **2016**.
26. EL-NAGGAR A., LEE S.S., AWAD Y.M., YANG X., RYU C., RIZWAN M., RINKLEBE J., TSANG D.C., OK Y.S. Influence of soil properties and feedstocks on biochar potential for carbon mineralization and improvement of infertile soils. Geoderma. **332**, 100, **2018**.
27. LEHMANN J., GAUNT J., RANDON M. Biochar sequestration in terrestrial ecosystems – a review. Mitig. Adapt. Strat. Gl. **11** (2), 395, **2006**.
28. JEFFERY S., ABALOS D., PRODANA M., BASTOS A.C., VAN GROENIGEN J.W., HUNGATE B.A., VERHEIJEN F. Biochar boosts tropical but not temperate crop yields. Environ. Res. Lett. **12** (5), 053001, **2017**.
29. World Reference Base for Soil Resources 2014. Update 2015. Available online: http://www.fao.org/3/i3794en/I3794en.pdf (accessed on 02.05.2019).
30. TOBIAŠOVÁ E., ŠIMANSKÝ V. Quantification of soil properties and their interrelationships effected by anthropogenic activity, SPU: Nitra, Slovakia, pp. 113, **2009** [In Slovak].
31. HORÁK J., ŠIMANSKÝ V. Effect of biochar and biochar combined with N-fertiliser on soil organic carbon content. Agriculture (Poľnohospodárstvo). **62** (4), 155, **2016**.
32. ŠIMANSKÝ V., HORÁK J., IGAZ D., JONCZAK J., MARKIEWICZ M., FELBER R., RIZHIYA E.Y., LUKAC M. How dose of biochar and biochar with nitrogen can improve the parameters of soil organic matter and soil structure? Biologia. **71** (9), 989, **2016**.
33. ŠIMANSKÝ V., HORÁK J., IGAZ D. Biochar as a potential tool for improving humus regime and aggregation of soils. Hydrology of Small Watersheds, Ústav pro hydrodynamiku: Prague, Czech Republic, **2017** [In Slovak].
34. IGAZ D., ŠIMANSKÝ V., HORÁK J., KONDRLOVÁ E., DOMANOVÁ J., RODNÝ M., BUCHKINA N.P. Can a single dose of biochar affect selected soil physical and chemical characteristics? J. Hydrol. Hydromech. **66** (4), 421, **2018**.
35. JURIGA M., ŠIMANSKÝ V., HORÁK J., KONDRLOVÁ E., IGAZ D., POLLÁKOVÁ N., BUCHKINA N., BALASHOV E. The effect of different rates of biochar and biochar in combination with N fertilizer on the parameters of soil organic matter and soil structure. Journal of Ecological Engineering. **19** (6), 153, **2018**.
36. ŠIMANSKÝ V., IGAZ D., HORÁK J., ŠURDA P., KOLENČÍK M., BUCHKINA N.P., UZAROWICZ L., JURIGA M., ŠRANK D., PAUKOVÁ Ž. Response of soil organic matter and water-stable aggregates to different biochar treatments including nitrogen fertilization. J. Hydrol. Hydromech. **66** (4), 429, **2018**.
37. ŠIMANSKÝ V., HORÁK J., KOVÁČIK P., BAJČAN D. Carbon sequestration in water-stable aggregates under biochar and biochar with nitrogen fertilization. Bulg. J. Agric. Sci. **23** (3), 429, **2017**.
38. ŠIMANSKÝ V., HORÁK J., JURIGA M., ŠRANK D. Soil structure and soil organic matter in water-stable aggregates under different application rates of biochar. Vietnam Journal of Earth Sciences. **40** (2), 97, **2018**.
39. SPOKAS K.S., REICOSKY D.C. Impacts of sixteen different biochars on soil greenhouse gas production. Annals of Environmental Science. **3**, 179, **2009**.
40. VAN ZWIETEN L., KIMBER S., MORRIS S., DOWNIE A., BERGER E., RUST J., SCHEER C. Influence of biochars on flux of N_2O and CO_2 from Ferrosol. Aust. J. Soil Res. **48** (7), 555, **2010**.
41. HORÁK J., ŠIMANSKÝ V. Effect of biochar on soil CO_2 production. Acta Fytotechnica et Zootechnica. **20** (4), 72, **2017**.
42. HORÁK J., KONDRLOVÁ E., IGAZ D., ŠIMANSKÝ V., FELBER R., LUKAC M., BALASHOV E.V., BUCHKINA N.P., RIZHIYA EY., JANKOWSKI M. Biochar and biochar with N-fertilizer affect soil N_2O emission in Haplic Luvisol. Biologia. **72** (9), 995, **2017**.
43. IGAZ D., HORÁK J., DOMANOVÁ J., ŠIMANSKÝ V., RODNÝ M., TÁRNÍK A. Effect of single dose of biochar application on soil water accumulation in the field experiment. Hydrology of Small Watersheds, Ústav pro hydrodynamiku: Prague, Czech Republic, **2017** [In Slovak].
44. IGAZ D., KONDRLOVÁ E., HORÁK J., ŠIMANSKÝ V. Biochar application and its effect on soil water content and corn vegetative development. International Scientific Conference dedicated to the 85th anniversary of the Agrophysical Research Institute "Trends in the Development of Agrophysics: from Actual Problems of Agriculture and Crop Production to Future Technologies, Agrophysical Research Institute: St. Petersburg, Russia, **2017**.
45. HORÁK J. Testing biochar as a possible way to ameliorate slightly acidic soil at the research field located in the Danubian lowland. Acta Horticulturae et Regiotecturae. **18** (1), 20, **2015**.
46. ŠIMANSKÝ V., JONCZAK J., PARZYCH A., HORÁK J. Contents and bioaccumulation of nutrients from soil to corn organs after application of different biochar doses. Carpath. J. Earth Env. **13** (1), 315, **2018**.
47. ŠIMANSKÝ V., HORÁK J., IGAZ D. Changes of soil sorption parameters after application of biochar and biochar with nitrogen fertilizer. International Scientific Conference dedicated to the 85th anniversary of the Agrophysical Research Institute "Trends in the Development of Agrophysics: from Actual Problems of

Agriculture and Crop Production to Future Technologies, Agrophysical Research Institute: St. Petersburg, Russia, **2017**.
48. ŠIMANSKÝ V., HORÁK J. Soil pH and sorptive parameters after additions of biochar and biochar with nitrogen. Agrochémia (Agrochemistry). **51** (2), 20, **2017** [In Slovak].
49. ŠIMANSKÝ V., HORÁK J., IGAZ D., BALAŠOV E.V., JONCZAK J. Biochar and biochar with N fertilizer as a potential tool for improving soil sorption of nutrients. J. Soil. Sediment. **18** (4), 1432, **2018**.
50. KONDRLOVÁ E., HORÁK J., IGAZ D. Effect of biochar and nutrient amendment on vegetative growth of spring barley (*Hordeum vulgare* L. var. Malz). Aust. J. Crop Sci. **12** (2), 178, **2018**.
51. CASADESÚS J., VILLEGAS D. Conventional digital cameras as a tool for assessing leaf area index and biomass for cereal breeding. J. Integr. Plant Biol. **56** (1), 7, **2014**.
52. KONDRLOVÁ E., HORÁK J., IGAZ D., DOBIAŠOVÁ D. The possibility of using digital images in assessment of plant canopy development and weed spread. Acta Horticulturae et Regiotecturae. **20** (2), 35, **2017**.
53. FERTAĽ P. Effect of biochar application on soil moisture and vegetation development index of corn. Master of Science thesis, Slovak University of Agriculture: Nitra, Slovakia, **2016** [In Slovak].
54. KRUPOVÁ M. Effect of selected soil additives on growth of agricultural crop. Bachelor thesis, Slovak University of Agriculture: Nitra, Slovakia, **2018** [In Slovak].
55. SIRÁŇOVÁ M. Effect of selected soil additives on growth of agricultural crop. Bachelor thesis, Slovak University of Agriculture: Nitra, Slovakia, **2018** [In Slovak].