CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Environmental Sciences

Department of Environmental Geosciences

The effect of contrasting biochar structure on hydraulic properties and its stability in soil

Diploma thesis

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DIPLOMA THESIS ASSIGNMENT

Bc. Václav Chroustovský

Environmental Geosciences

Thesis title

The effect of contrasting biochar structure on hydraulic properties and its stability in soil

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Objectives of thesis

The application of various biochars will significantly affect soil hydraulic properties. The stability of various biochars will be represented by minimum leaching of the DOC.

Methodology

First, review of presented studies related to the effect of biochar to soil hydraulic properties will be provided.

Consequently, the effect of contrasting biochars as well as their particle size will be assessed using laboratory pot experiment under constant conditions of soil moisture. Such prepared ”growth” soil profile will then be used for analyses of saturated hydraulic conductivity and detection of the values of individual retention curves. Additionally, dissolved organic carbon will be sampled using rhizones and such obtained pore water will then be analysed using TOC analyser.

The proposed extent of the thesis

50-60

Keywords

biochar, retention curves, saturated hydraulic conductivity, structure, DOC leaching

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Recommended information sources

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Prague on 13. 04. 2017

„ Hereby I declare that I elaborated this Master thesis independently, under the supervision of Mgr. Lukáš Trakal, Ph.D. I have listed all literature from which I have acquired information. “

In Prague

Day: 18.4.2017 Václav Chroustovský

Abstract

This thesis aims to examine and assess the effect of contrasting biochars on the hydraulic properties of fluvisols. Two experiments were conducted, with regards to soil hydraulic properties, in order to obtain such results that could provide more detailed information about the behavior of biochar in fluvisol collected at given site. For that, a set of boxes with amended soil was prepared. The soil was amended with biochars, which had different physico-chemical properties, and were produced from different types of feedstocks and at different pyrolytic conditions.

The first experiment, focusing on measurement of the saturated hydraulic conductivity of amended soil, was performed in 3 trials at 1 wt % and 2 wt % application rate. The results showed that the 1 % application of plant biochar had strongly influenced the saturated hydraulic conductivity, where the difference between values of saturated hydraulic conductivity at 1 % application of plant biochar and the control sample was statistically significant (*p value*=0.037), however, this results was obtained only in 3rd time-step, in other two time steps the differences in measured values of treated samples compared to control samples were not statistically significant. Moreover, the increasing amount of biochar did not improve the hydraulic properties of amended soil.

The second experiment focused on water holding capacity of soil amended with biochar, and was performed at 1 wt % and 2 wt % application rates. Measured data showed inconsistency of the results, where no obvious trend was observed, except the volumetric moisture content at high suction pressures – i.e. the soil amended with biochar indicates the ability to hold hygroscopic water – where the highest content of moisture was measured for samples with 1 % application of plant biochar. In all cases the water holding capacity of amended soil was increased.

Thus, the results of both experiments, have partially confirmed what was hypothesized.

Key words: biochar, retention curves, saturated hydraulic conductivity, structure, DOC leaching

Abstrakt

Tato diplomová práce si klade za cíl zjištění a vyhodnocení vlivu kontrastních biocharů na hydraulické vlastnosti fluvizemě. Za cílem získání více podrobných informací, o chování biocharu ve fluvizemích, byly provedeny dva experimenty ze zeminy odebrané v dané lokalitě. K tomu bylo připraveno několik boxů se zeminou smíchanou s biocharem, který měl rozdílné fyzikálně-chemické vlastnosti a byl získán z jiných výchozích produktů a za odlišných pyrolytických podmínek.

První experiment, zaměřený na měření saturované hydraulické vodivosti půdy ošetřené biocharem, byl proveden ve třech krocích, při aplikaci 1% a 2% podílu biocharu v půdě. Výsledky ukázaly, že aplikace rostlinného biocharu v 1% poměru významně ovlivnilo saturovanou hydraulickou vodivost, kdy rozdíl průměrů hodnot mezi vzorky ošetřenými 1 % rostlinného biocharu a kontrolními vzorky, byl statisticky významný (*p value*=0.037). Nicméně tento výsledek byl získán pouze ve třetím časovém kroku. V ostatních dvou krocích rozdíl naměřených průměrů takto ošetřených vzorků a kontrolního vzorku nebyl statisticky významný. Kromě toho, zvyšování podílu biocharu v půdě nevedlo ke zlepšení hydraulických vlastností ošetřené půdy.

Druhý experiment byl zaměřen na retenci vody v půdě ošetřené biocharem, při aplikaci 1% a 2% podílu biocharu v půdě. Naměřené hodnoty vykazovaly nekonzistentnost, kde nebyl pozorován žádný určitý trend, kromě objemové vlhkosti ve vysokých sacích tlacích, t.j. půda ošetřená biocharem vykazovala schopnost držet hygroskopickou vodu, přičemž nejvyšší objemová vlhkost byla naměřena pro vzorky ošetřené 1% aplikací rostlinného biocharu. Ve všech případech ošetření půdy bicoharem, se retenční kapacita půdy zvýšila.

Tudíž výsledky obou provedených experimentů částečně potvrdily stanovené hypotézy.

Klíčová slova: biochar, retenční čáry, saturovaná hydraulická vodivost, struktura, vyluhování DOC

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1. Introduction

Generally the Earth system is composed of many individual units and parts, which interacts between each other and are connected together. Each such part is of absolute necessity for functioning of the rest as a whole system. One of those units is soil. Soil provides not only a habitat for terrestrial fauna, but also plays a key role in the global water cycle. Different types of soils have different ability to retain water. This characteristic is crucial for plant life, development of flora, and all processes. It is well known fact that the presence of organic matter in soils effects the water holding capacity of soils. One of the representatives of organic matter is biochar.

Biochar became widely discussed topic in the field of science in recent years. Particularly in connection with sequestration of carbon into soils, which is undoubtedly one of the up to date science topic. Current daily production of carbon in various forms is so great that remaining unchanged could lead to serious troubles in the future. On the other hand, some scientists claim that such a big withdrawal of carbon and subsequent storage of it in soils may lead to misbalances in global carbon cycle. In both cases, the way how we influence the natural processes, such as element cycles, climate, erosion, and many others, has exceeded the sustainable frontier. Now it lays within the hands of whole mankind to take responsibility for our past, current and future steps.

In last few decades many scientists and researchers has focused their research not only on sequestration of carbon, but also on the role that carbon plays in the whole environment, which as a complex system that includes soil chemistry, soil mechanism, soil water retention, plant growth, erosion and others, must be considered as such and not as an isolated unit.

Biochar, as a product of pyrolysis of carbon rich biomass, is not a new invention, is has been used throughout the mankind history as a soil amendment that improves soil conditions for plant growth and potentially stabilizes the soil, however, the term biochar itself was coined in recent history. Furthermore, its production was utilized on regular basis because it was commonly used in agriculture all around the world.

Today’s research is very specific and deep, yet the results are often argued among the scientific community, mainly due to contrasting results. The experiments are conducted either *in situ* or in laboratory conditions. While the *in situ* experiments resulted mostly in uncertain data, showing a big variety of factors influencing the field experiment, the laboratory experiments are often focused on certain characteristics of the interaction of biochar with the medium (soils). Given to that, both methods (*in situ* and laboratory) have some advantages and must be regarded with respect to the method used. Another thing is its application *in situ*, especially when one consider its use on a great areas. Problems arise with incorporation of biochar into soil, and different region and climate often require special approach. Every type of soil behaves differently, thus the biochar has to be produced in a way that suits given conditions the best.

This thesis is focused on the effects of contrasting biochar on saturated hydraulic conductivity and soil water holding capacity in a particular type of soil. In this study the application of biochar to fluvisols, made of different feedstocks, was examined and evaluated. The core of the experiments was to examine how it effects the hydraulic properties, and also improvement of retention properties of fluvisols, thus creating a potential way to mitigate droughts. The samples were treated under the same conditions in several trials in order to obtain representative data, which were subsequently statistically analyzed. It was hypothesized that addition of biochars produced under different conditions, will affect the hydraulic properties of given soil, respectively that the measurements will result in higher water holding capacity and will decrease the saturated hydraulic conductivity.

2. Aims of the thesis

The aim of this thesis is to evaluate effects of contrasting biochars, which were added to fluvisol at two application rates: (i) 1 wt % rate and (ii) 2 wt % rate; on the soil water holding capacity, and the saturated hydraulic conductivity of given soil. The assessments is based on experiments designed for measuring of saturated hydraulic conductivity and water holding capacity of the amended soil.

3. Literature review

3.1.Biochar

The biochar is generally used as a soil amendment, which improves the soil properties. According to Sohi et al. (2010), biochar is an organic material, rich in carbon, produced by thermal decomposition of plant-derived biomass under conditions of partial or total absence of oxygen. It is characterized by a low bulk density, because of its quite porous structure, and large specific surface area (Abel, et al., 2013). Another interpretation is by Lehman and Joseph (2009), who defines it as a product of pyrolysis of biomass used as a carbon storage, soil amendment or filtration of percolating soil water. Another use of it is as a soil amendment which is applied to soils to sequester carbon (Verheijen, et al., 2010).

The wide range of its unique properties make this product suitable for improving soil physical properties (i.e. structure of soil, pore size distribution, bulk density), hydraulic properties (i.e. hydraulic conductivity, soil water retention, etc.) and chemical properties (i.e. pH, CEC, EC etc.). Also, it can increase plant growth in arable soils (Liu, et al., 2014; Liu, et al., 2011). It influences crop production by water- and nutrient-holding capacity (Ahmed, et al., 2016), where it adsorbs nutrients, thus decreases nutrient leaching, and renders the nutrients to plants (Rogovska, et al., 2014; Kameyama, et al., 2012). Another utilization of biochar is to use it as a treatment system for removal of organic contaminants – carbon sequestration – and inorganic contaminants – e.g. metals (As, Cd, Cr, Cu, Ni, Pb, Zn) – from surface water, underground water, soils, and sediments (Liu, et al., 2016; Abel, et al., 2013).

The properties of biochar are dependent on the material of feedstock and the production conditions – e.g. oxygen level, duration of combustion, temperature of pyrolysis, pressure during processing, and heating rate (Gundale & DeLuca, 2006; Oberlin, 2002). According to Lua et al. (2004) observations the pyrolysis temperature and pyrolysis heating rate are having the most significant effect on the final properties of biochar – note: those finding are directly relevant to given processing conditions and feedstocks. Furthermore properties of biochar and efficacy depends on type of feedstock used. The feedstock properties and pyrolysis conditions contribute to the final biochar's properties – i.e. surface chemistry, composition, nutrient composition, adsorption capacity, pH, cation exchange capacity (CEC), physical structure (Ahmed, et al., 2016; Cimo, et al., 2014).

Application of biochar to soil significantly influences the physical and chemical properties of soils, respectively volume, shape of the soil pores and diameter – these key parameters, which characterize the porous environment, determine the water retention and water movement. Apart from that, the chemical composition, surface characteristics, together with physical and chemical stabilization mechanisms determine the effect of biochar on function of soil (Horel, et al., 2015; Sohi, et al., 2010). Kolb (2007) postulates that biochar is related to improved soil aeration and soil structure in fine-textured soils. However, the long-term effects of biochar are not fully understood yet, there are some uncertainties about it, for example it potentially can lead to soil pores clogging due to disintegration of biochar material (Verheijen, et al., 2010). Moreover, the processes and mechanisms by which biochar influences soil pore size distribution still remains unclear or have not been established (Verheijen, et al., 2010).

Main factors which control the properties of final product (biochar) are composition, particle and pore size distribution, pyrolysis conditions and characteristic of feedstock. The resulted biochar properties are typical by high heterogeneity, namely between biochar that were produced from different feedstocks and under different pyrolysis conditions (Sohi, et al., 2010).

Biochar has notable effects on plant available water content (PAWC) and water holding capacity (WHC) via the enhancing the total pore volume in soils and decreasing the bulk density we observe an increase in water content at the permanent wilting point. By its low bulk density and solid density it can improve soil density, respectively decrease the soil density and increase soil porosity. Its capacity to store water unavailable to the plants is due to its high porosity, related to high specific area, which consequently leads to a high capability for water adsorption (Kinney, et al., 2012; Verheijen, et al., 2010; Vartapetyan & Voloshchuk, 1995; Zhang, et al., 2012). With regards to the PAWC, most plants are not able to extract soil water from pores smaller than 0.2 μm, however, biochar potentially increases the number of pores between 0.03-0.0003 μm in the amended soil. Therefore, the higher porosity does not necessary leads to improvement of conditions of PAWC. Even though, the total porosity might be higher, soil bulk density lower, the PAWC might remain unchanged (Verheijen, et al., 2010). The improvement of soil water retention by biochar application is rather expected in soils containing large amount of macropores or coarse-textured soils (Verheijen, et al., 2010). Nevertheless, the hydraulic behavior of biochars does not ultimately determine the behavior of soil amended with biochar (Kinney, et al., 2012). Soil hydraulic properties are potentially affected by biochar effects on soil aggregation through the interaction with soil organic matter, minerals, and microorganisms (Asai, et al., 2009). PAWC is a key characteristic that is important for crop production and for plant nourishment in general. Figure 1 shows the hypothesized effect of biochar on plant available water on the background of soil water retention curve (RETC).

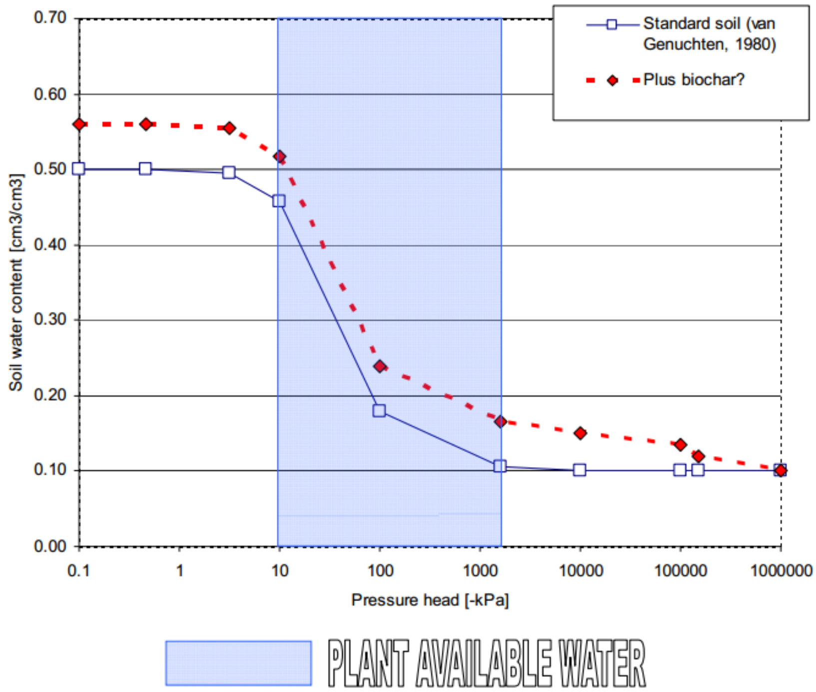

Figure 1 - Soil water retention curve (Van Genuchten, 1980) and hypothesized effect of biochar after application to soil (Verheijen, et al., 2010).

3.1.1. Feedstocks

Biochar is produced out of biomass material, such as wood, woodchips, crop residues, manure, and others (Ahmed, et al., 2016). The production and regular supply of large amount of biochar for agricultural soils is a challenge in means of providing a sustainable and consistent feedstock (Downie, et al., 2012). Most of the waste biomass that can be used as a feedstock for large-scale biochar production, is split between several competing end-users, while the small-scale production is usually dependent on seasonal biomass production cycle. Before the feedstock can be processed it needs to be dried and the size must be reduced, consequently the feedstock particle size and moisture contents need to be optimized (Singh, et al., 2010). There are many key factors which need to be taken into account for the mass production of biochar. However, so far there is not even a thought of centralized and mass production of biochar because of very specific requirements for biochar application to certain type of soil or for different purposes, where for each purpose, there is need of a biochar with specific properties in order to achieve desired results. Thus the choice of feedstock is crucial for subsequent biochar application.

Generally the requirements of fast heating rates need smaller feedstock particles to provide the mass and heat transfer, for the slow pyrolysis rates, a larger particles might be used – i.e. in order to facilitate fast pyrolysis the feedstock is processed to powder or dust, this will yield a very fine biochar (Downie, 2011). Jindo et al. (2014) observed that the type of feedstock affects the biochar yields and the content of volatile matter, when the woody biochar produced at relatively low-temperature pyrolysis had high volatile matter content, which can be attributed to the presence of lignin in woody feedstocks, which can resists to pyrolytic decomposition at 400 °C.

Table 1 provides overview of common biochar feedstocks and its physical properties at given pyrolysis temperature. The type of feedstock basically determines the biochar behavior in soils and its final application because the nature of feedstock designates the properties of biochar (Jindo, et al., 2014). For demonstration of unique properties of biochar produced from different feedstock, Singh et al. (2010) observations showed that the soil cation-exchange capacity of manure-based biochar is higher than that of wood biochar (Eucalyptus), whereas the treatment of soil with manure-based biochar results in lower saturated hydraulic conductivity than treatment with woodchip biochar (Lei & Zhang, 2013). Jindo et al. (2014) observations showed that the different feedstocks – woody feedstock and rice residues feedstock - resulted in increasing difference in microporosity, as the pyrolytic temperature was gradually increased.

Feedstock	Pyrolysis temperature [°C]	Pore volume [cm^3/g]	Surface area [m2/g]	References
Malt spent Rootlets	400	3.4	0.016	Manariotis et al. (2015)
	800	340	0.21	
Hardwood	300	0.06	N/A	Xiao and Pignatello (2015)
	500	0.21	N/A	
Wheat	400	0.016	10.15	Manna and Singh (2015)
	600	0.034	20.38	
Biosolids	650	N/A	395	Kaudal et al. (2015)
		N/A		
Wood	350	N/A	1	Brewer et al. (2014)
	800	N/A	317	
Rice husk	350	N/A	32.7	Claoston et al. (2014)
	650	N/A	261.72	
Empty fruit bunch	350	N/A	11.76	
	650	N/A	28.2	
Rubber wood	300	0.0034	1.399	Shaaban et al. (2014)
	700	0.0097	5.49	
Medicinal herbs	300	4.45	0.0075	Yuan (2014)
	700	11	0.0178	
Coal tailings	400	N/A	2.7	Tremain et al. (2014)
	800	N/A	75.3	
Pine needle	100	N/A	0.65	Tang et al. (2013)
	700	N/A	490.8	
Cotton seed hulls	350	N/A	4.7	
	800	N/A	322	
Oakwood	350	N/A	450	
	600	N/A	642	
Corn Stover	350	N/A	293	
	600	N/A	527	
Broiler litter manure	350	N/A	59.5	
	700	N/A	94.2	
Soybean stalk	300	N/A	144.17	
	700	N/A	250.23	
Pine needles	300	N/A	4.09	Ahmad et al. (2013)
	700	N/A	390.52	
Sewage sludge	400	N/A	33.44	Méndez et al. (2013)
	600	N/A	37.18	
Swithgrass	450	N/A	5.89	Kim et al. (2013)
	800	N/A	52.27	
Bagasse	400	0.03	14.4	Kameyama et al. (2012)
	800	0.16	219	
Switchgrass	250	N/A	0.4	Ippolito et al. (2012)
	500	N/A	62.2	
Maize	300	N/A	1	Wang et al. (2015)
	600	N/A	70	

Table 1- Biochar surface area and pore volume - influence of type of feedstock and pyrolysis temperature (Amended from Ahmed et al. 2016).

3.1.2. Methods of pyrolysis

Generally the biochars produced in fast reactors (high heating rates) have different physical properties than those produced at slow pyrolytic conditions (Downie, et al., 2009). It has been shown that the heating rate, pressure level during the processing and residence time are determinant factors, influencing generation of finer biochar particles. Cetin et al. (2004) observed that in order to gain fine biochar material, a higher heating rates (up to 105-500°C sec^{-1}), finer feedstock particles and shorter residence time are required to facilitate such production. On the other hand, findings of Downie (2011) showed that coarser biochars are produced when larger feedstock particles are used and pyrolysis is held at slower heating rates (5-30°C sec^{-1}).

As was mentioned, the production conditions and type of feedstock determine the properties of biochar. For instance, biochar produced under high temperature has higher porosity, which increases with temperature, because of escape of gasses and volatilization of tars that are present within the pores (Cantrell, et al., 2007), while biochars produced at low-temperatures pyrolysis have high content of volatile matter (Robertson, et al., 2012). The increasing porosity due to higher temperatures of pyrolysis was observed by many authors (e.g. Brantley, et al. (2015)). Production of biochar under temperature of 300 °C results in biochar with cellulose compounds, which are broken down at higher temperatures. Biochar produced under such conditions retains more soil nutrients, due to higher surface area for nutrient to be adsorbed. Biochar produced under the temperature exceeding 450 °C, subsequently added to soil, can improve the internal drainage of the soil and provides water availability to plants. On the other hand, sometimes the biochar produced under the temperature 450 °C repels water (Glaser, et al., 2002; Page-Dumroese, et al., 2015). The same results were obtained by Kinney et al. (2012) where biochars produced under the pyrolytic temperature of 450 °C contained more water repelling organic compounds. Contrary to this observation with repellency of biochar produced at low-temperature, were results of biochar produced at high-temperature pyrolysis, which Ajayi et al. (2016) used for their experiments; the biochar was slightly hydrophobic with an average repellency index, $R_{index} = 2.23$. Thus the pyrolytic condition and type of feedstock drive variations in hydrophobicity (Kinney, et al., 2012).

Biochar produced at low temperatures have lesser water retention and infiltration at their saturation point than biochar produced at high temperatures, greater than 400 °C. This might be related to influence of high production temperature, which affects biochar pore volume and pore tortuosity (Kameyama, et al., 2014). On the other hand, low-temperature pyrolysis yielded higher amount of biochar than high-temperature pyrolysis (Jindo, et al., 2014). Generally high-temperature pyrolysis production of biochars results in lower total surface charges, higher specific surface areas, pH, porosity and ash content (Bagreev, et al., 2001; Novak, et al., 2009). In compliance with those observations Lei and Zhang (2013) reported that the highest temperatures of pyrolysis resulted in increased saturated hydraulic conductivity (K_{sat}).

Kinney et al. (2012) postulated that the biochar reaches optimum hydrologic properties, depending on feedstock, at temperatures between 400 and 600 °C.

Mohamed et al. (2016b) has proved that the conventional heating at low temperatures is less efficient than the microwave-assisted pyrolysis, which produces biochar with larger surface area and more porous structure, due to higher heating rate and genuine microwave heating process. Thus microwave heating might be a potential way for making more porous biochar (Mohamed, et al., 2016). For further details Singh et al. (2014) provides comprehensive table, which summarize recently developed types of kilns, along with their general characteristics. Figure 2 represents relationship of biochar structure and treatment temperature.

Description of slow and fast pyrolysis by Garci-Perez et al. (2010):

Slow pyrolysis. As a slow pyrolysis reactor is considered any reactor, which utilizes particles larger than 2 mm – kilns, rotors, converters, rotating drum reactors. Heating of biomass is very slow – i.e. the heating rate is around 5-7 °C/min. Typically produces more char than fast pyrolysis, that is 25-35 mass %.

Fast pyrolysis. Due to low thermal conductivity of lignocellulostic of feedstock, the reactors can utilize only small particles. Heating of biomass is very fast – i.e. heating rates over 300 °C/min. Fast pyrolysis that can utilize particles up to 50 mm is called *ablative pyrolysis*. This is possible due to rapid removal of low thermal conductivity layer of biochar that surrounds the particle. The reactors are (i) fluid bed reactors, (ii) rotating cone, (iii) vacuum pyrolysis reactors (Ronsse, et al., 2013).

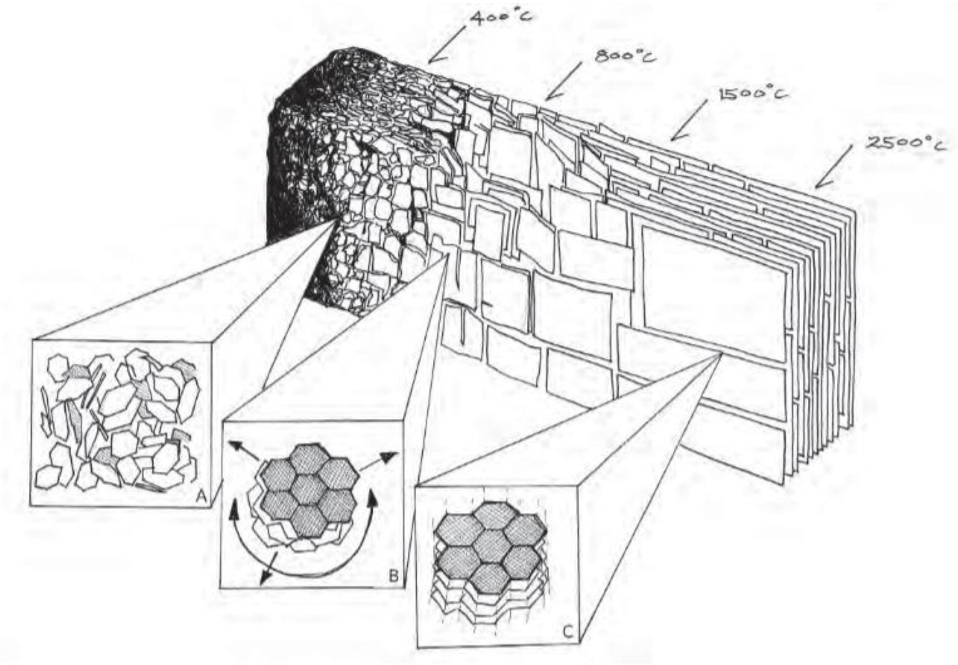

Figure 2 - Ideal biochar structure development with highest treatment temperature (HTT): (A) increased proportion of aromatic carbon, highly disordered in amorphous mass; (B) growing sheets of conjugated aromatic carbon, trubostratically arranged; (C) structure becomes graphitic with order in third dimension (Downie, 2011)

3.1.3. Physical and physico-chemical characteristics of biochar

Particle size distribution. It is mainly influenced by the nature of the feedstock and pyrolytic conditions – e.g. coarser biochars are produced from wood-based feedstocks while fine and more fragile biochar is produced from manures and crop residues. It is probable that the particle sizes of feedstock will be larger than the final product - biochar (Sohi, et al., 2009; Downie, 2011). Downie (2011) observed decrement of feedstock resistance to attrition during the production process, which resulted in sawdust-based and woodchips-based biochar's particle size was decreasing as the pyrolytic temperature was increasing – i.e. with higher temperature the particle sizes tends to decrease.

Porosity. It is calculated from the difference in densities (Brewer, et al., 2014).

$$Porosity = \left(1 - \frac{\rho_e}{\rho_s}\right) \qquad (1)$$

Currently there is no technique, that can precisely measure pore volume, and thus the effective biochar porosity characterization remains elusive (Brewer, et al., 2014). Among the most common methods for measuring the porosity is mercury porosimetry, gas sorption - carbon dioxide adsorption, and nitrogen adsorption, however these methods are related only to sub-micro pores and micro- and macro-pores (meso-pores). The adsorption methods cannot provide information about pores larger than macropores (meso-pores) (Brewer, et al., 2014; Sun, et al., 2012; Brewer, et al., 2009). Non quantitative methods of measuring the porosity and visualizing the larger pores, such as stereological method, is based on image analyses, sectioning and 3-D reconstruction. Scanning electron microscopy (SEM) methods are often used for detection of biochar macropores (Weibel, et al., 1966; Brewer, et al., 2009; Bird, et al., 2008). Recently Brewer et al. (2014) developed new methods to measure biochar porosity, based on density measurements – skeletal density and envelope density – where the volume of known mass is measured by displacement technique. This method quantify biochar porosity at micro- to macro-pore size. Total porosity of biochar is reported to be up to 80 vol.% (Abel, et al., 2013). According to Głąb et al. (2016) results, the total porosity of soil is increased with the increasing biochar application rate – i.e. and the higher the application rate is, the higher is the total porosity. Pores that have key role in surface area of biochars are micropores (<2 nm), which are responsible for high adsorptive capacities (Rouquerol, et al., 1999; Mohamed, et al., 2016). To illustrate this relationship, Downie (2011) provides explicit figure 3:

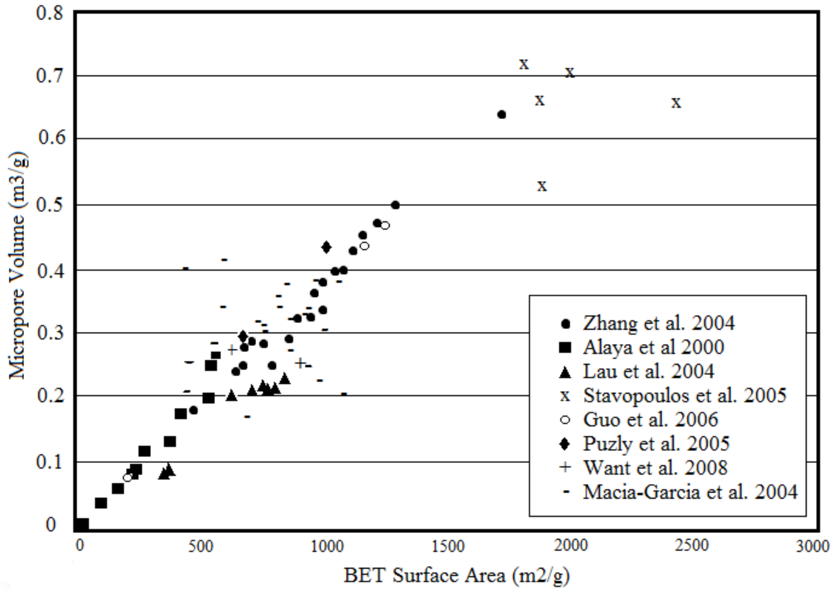

Figure 3 - Demonstration of relationship between micro-pore volume and surface area of biochar (Amended from Downie et al. 2009).

Density of biochar. Two type of density are recognized, bulk density (BD) – it is a measure of the mass over the volume of material including intra and inter-particle pores; and solid density (SD), which is related to the degree of packing of the C structure. Both depends on the type of feedstock and pyrolysis conditions (Pandolfo, et al., 1994; Downie, 2011). Findings of Brown et al. (2009) showed direct dependency of density on the ultimate pyrolytic temperature. Also, biochar tends to decrease the bulk density (BD) of soils (Andrenelli, et al., 2016; Barnes, et al., 2014) – i.e. the smaller the particles, the higher the BD (Głąb, et al., 2016).

Surface area. This property is determined by the feedstock type and pyrolytic conditions (Wang, et al., 2015). It is one of the crucial physical characteristic of biochar for improvement of soil characteristics – e.g. water holding capacity and soil adsorption. Findings of Wang et al. (2015) showed that the wood and grass biochars that were produced at relatively low temperatures (300°C, 450°C) had small surface area ranging from 0.1-15 m^2/g whereas biochars made from loblolly pine and citrus had surface area 209 and 183 m^2/g. According to other studies (Lei & Zhang, 2013; Gaskin, et al., 2008; Ronsse, et al., 2011; Jindo, et al., 2014) the surface area of biochar produced at high temperatures increased, compared to the production at lower temperatures. Lehmann (2007) reports the same phenomenon when biochar is derived from high temperature pyrolysis, then its structure is characterized by a large surface area. On the other hand, researchers are often confronted with drastic loss of structural complexity, this is accounted to fusion, plastic deformation, high heating rates, high ash content, and long retention times and it is followed by loss of surface area and porosity. In general terms the surface area increases with temperature of pyrolysis until the temperature of deformation is reached, this is followed by decrease in surface area (Downie, 2011).

Water holding capability (WHC). This property give information about the behavior of biochar, when exposed to water, in porous media and during its presence in the media (Allaire, et al., 2015). Due to high amount of small pores, biochar has high capacity to retain water (Major, et al., 2009). Many biochar factors are associated with the improvement of water holding capacity, e.g. porosity structure, specific surface area total pore volume, and others (Zhang & You, 2013). In general, the biochar improves soil water retention (Głąb, et al., 2016). Findings of Zhang and You (2013) showed significant positive correlation between biochar water holding capacity and total pore volume, however, no obvious correlation was observed between wood biochar and the surface area. Głąb et al. (2016) concluded that the scale of water retention effect depends on biochar particle size, its rate and type of feedstock. Findings of Brantley et al. (2015) are in correspondece with this statement; their results showed that biochar produced from poultry litter retained more water, at given water potential, than biochar produced from woodchip. The average biochar pore diameter has impact on water holding capacity, through adding the biochar to soil the voids and large pore spaces, between soil particles, are reduced and the soil surface is increased, this directly reduce the loss of water by gravitational force. On the other hand macropores (> 80 μm) can play role, by increasing the flow of water through the pores and soil profile, in decreasing the water holding capacity (Mohamed, et al., 2016; Major, et al., 2009). Hardie et al. (2014) conducted in situ experiments and the obtained results showed no significant effect on moisture content, field capacity, plant available water capacity, soil water retention parameters, permanent wilting point. On the other hand it significantly lowered bulk density, significantly higher soil water content at -0.1 kPa. However, they attributed these effects to earthworm activity, who formed large macropores (> 1200 μm).

Electrical conductivity (EC). Ojeda et al. (2015) and Burrell et al. (2016) reports that after application of biochar the EC was enhanced.

Cation exchange capacity (CEC). It is being considered as indirect measure of soil ability to hold water (Major, et al., 2009). This is supported by findings of Mohamed et al. (2016) and presented in figure 4. Mohamed et al. (2016) results showed significant increases of soil CEC after application of biochar, probably due to biochar oxidation. On the contrary, Laird et al. (2017) in their research observed a decrease in average CEC values, however, they noted that the cause of such behavior is not clear.

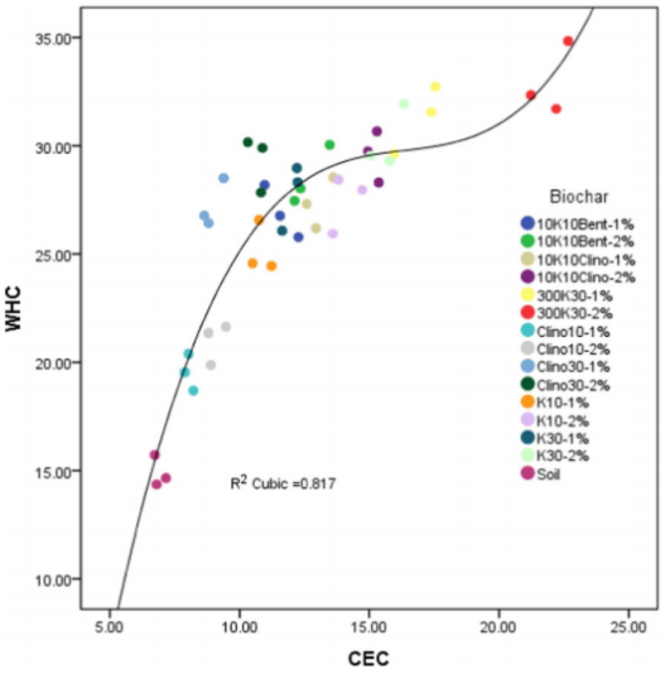

Figure 4 - Correlation between CEC and WHC at different biochar application rates (Mohamed, et al., 2016).

pH. Generally the pH value depends on production conditions of biochar and the type of feedstock used. The pH value of type of feedstock does not indicate whether the buffering capacity of biochar will be sufficient to maintain its pH (Allaire, et al., 2015). Verheijen et al. (2010) postulated that the pH value of biochar is relatively homogeneous, typically > 7 (neutral to basic). According to Wang et al. (2015) observations the pH increased with pyrolysis temperature due to increase of alkaline cation at high pyrolysis temperature. The similar results were obtained by Ronsse et al. (2011) who observed pH increase as the pyrolytic process was longer and the treatment temperature higher. Novak et al. (2009) observations provided the same results. Jindo et al. (2014) experiment showed that the pH value of biochar increased with temperature, probably due to relative concentration of non-pyrolyzed inorganic elements (Novak, et al., 2009). Findings of Chan and Xu (2009) of a mean pH value showed that generally higher pH values were measured in biochars produced from poultry litter feedstock while the lower pH values were measured in biochars gained from tree bark and green waste feedstocks, the obtained pH range was 6.2-9.6 with a mean pH value 8.1.

3.2.Saturated hydraulic conductivity

Saturated hydraulic conductivity, K_{sat}, describes water movement through saturated porous media, it can be measured or it can be estimated using empirical or theoretical models. In general, the saturated hydraulic conductivity is a characteristic, which describes state of system where the infiltration rate reaches a steady state condition (McCuen, 2003). K_{sat} is one of the key variable of hydropedology, which determines water relationship for plants, agricultural use of particular soil types and potentials for leaching of various elements (West, et al., 2008). Furthermore, it directly influences the amount of runoff and is directly related to soil effective porosity (Ahuja, et al., 1984).

K_{sat} can be measured directly (laboratory or *in situ* methods) or indirectly. The laboratory measurements are done with constant head method (used for permeable and semi-permeable samples) or falling head method (used for less permeable samples).

With regards to biochar, the effects on the saturated hydraulic conductivity of soils is dependent on its characteristics and application rate, and also on the type of soil, and its characteristics (namely texture) (Andrenelli, et al., 2016). Consequently the K_{sat} is either reduced or increased. For instance, Ajayi et al. (2016) observed decrease of K_{sat} in the sandy soil as the biochar amount was increased. The same was observed by Uzoma et al. (2011). On the contrary, in Ajayi et al. (2016) other experiment, the application of biochar to finer sandy loamy silt the K_{sat} was slightly increased, due to the expected rearrangement of the particles and the level of pore organization (Sun, et al., 2013). The same findings were obtained by Herath et al. (2013). Barnes et al. (2014) results of application of biochar showed an increase in K_{sat} in clay-rich soil, in contrast to this when the biochar was added to organic-rich soil the K_{sat} decreased. The authors concluded that the differences are attributable to different application rates, biochar grain size, internal structure, and soil properties or to high field capacity of biochar. Thus, the K_{sat} in coarser soils decrease with application of biochar and in the fine-grained clay soils the biochar is able to increase porosity and permeability (Barnes, et al., 2014).

3.3. Soil water holding capacity

Soil water holding capacity is described by soil-water retention curve that tell us the amount of water retained at a given matric potential (Tuller & Or, 2004). Soil water holding capacity might be expressed by graph of RETC that represents relationship between pressure head and water content – figure 5. To find a curve of pressure head (h) versus soil water content (θ) we apply different pressure heads (step by step), while at the same time the moisture content is measured (Joseph, 2010).

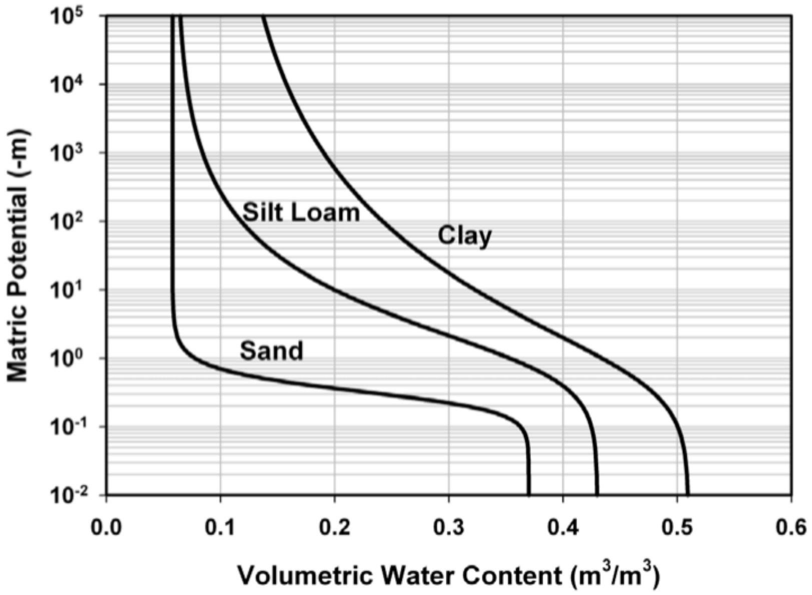

Figure 5 - Soil water characteristic curves for soils of different texture (Tuller & Or, 2004)

Some researchers suggested that the water holding capacity of soils is dependent on several variables – i.e. distribution of soil pores, aggregation, soil organic content and distribution of soil pores (Verheijen, et al., 2010; Downie, et al., 2009; Major, et al., 2009). Usage of organic matter seems to favor soil water retention, through increase in soil porosity and pore size diameter (Lehmann, 2007). However, the specific mechanisms how biochar application influences the water retention are poorly understood (Sohi, et al., 2009) because most of the studies examining the effects of biochar on soil water availability and soil water content has been conducted on repacked rather than *in situ* soils, non-agricultural soils (coarser soils, sandy soils), at too high application rates for agriculture impracticable, and other reasons. Out of these is the main concern usage of sieved repacked soils in which hydraulic properties (such as hydraulic conductivity, plant available water content, field capacity) are artefact of the process of repacking (Hardie, et al., 2014b). Kutílek et al. (2006) states that the water retention at lower suction pressures depends on the content of larger pores (this content is mainly affected by soil structure), while the water retention at higher suction pressures is influenced mainly by soil texture and surface area. Hardie et al. (2014) proposed that soil water retention is influenced by biochar (through soil porosity) via three mechanisms:

I. Creation of packing
II. Direct pore contribution from pores within the biochars
III. Through improved persistence of soil pores due to increased aggregate stability

Zwart & Hummelink (2014) concluded that at least a 10% application rate of biochar is needed in order to improve sandy soils and to obtain positive practical implications. However, application of such amount of biochar is arguable due to its long term effect in the environment, the quantity of feedstock required for production of such amount of biochar for one hectare and its subsequent incorporation to soils. In their other observations Zwart & Hummelink obtained results that showed no effect of biochar at application rate 0.5% on availability of water.

3.4.Fluvisols

The fluvisols are not well developed soils, typically with horizons A directly over C. This type of soil is formed on the water borne sediments which are typical for the flood plains rivers, and the shorelines of seas and lakes – i.e. the soils are formed on river, lacustrine and marine deposits (Paz, et al., 2008). The evolution stage of fluvisols depend on the direct exposition to hydrological variations, also the soil texture depend on the subsoil horizons (Kercheva, et al., 2017). The stratification of sediments is commonly present. The mineral composition and texture is dependent on conditions at given locality.

The soil structure, defined by pore systems and solid components, is a main factor of soil physical status. The fluvisols are characterized by high vertical and horizontal heterogeneity, which is result of varying characteristics of alluvial sediments, regime of deposition, land use and distance to river (age of formation). The evolution stage of fluvisols is basically in the initial states, making them unstructured (Kercheva, et al., 2017; Ciric, et al., 2012).

The available water storage, mean radius and volume of pores are influenced by local factors (Kercheva, et al., 2017). Total porosity, infiltration rate and soil organic matter are strongly dependent on the land use, as Gajić (2013) found the conversion of forest fluvisols to grassland and to arable lands has significantly decreased these properties in the top 20 cm of soil.

4. Materials and methods

4.1.Soil preparation and characteristics

Soil was collected at experimental field of Faculty of Environmental Sciences (49.7201722N, 14.0129314E) near village Trhové Dušníky, close to city Příbram. The experimental field lays at 440 m a.s.l and is situated on the banks of river Litavka as shown in the figure 6. The soil was collected at the depth ranging from 10 to 30 cm below the surface. The site is specific for regular flood events. In order to work with the soil it was air-dried at room temperature and then sieved (>2 mm) and homogenized.

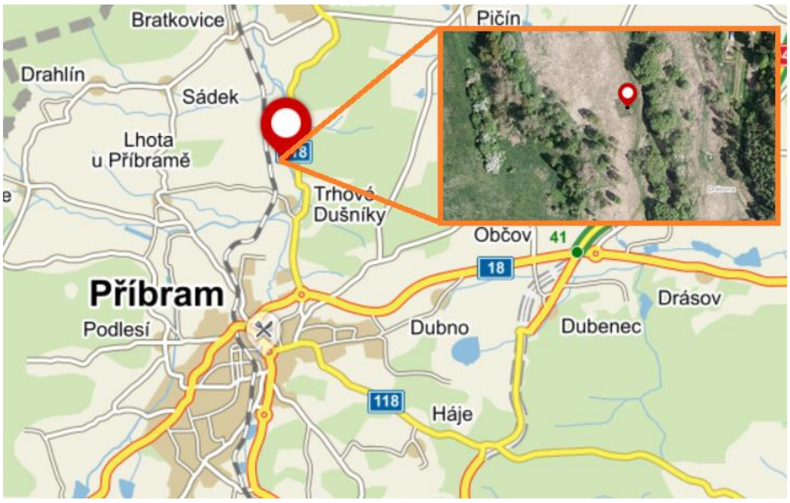

Figure 6 - Map showing the location of experimental field (source: www.mapy.cz)

4.2.Biochar preparation and characteristics

The biochars used in the experiment were produced from mixture of hardwood and softwood, and from Miscanthus x giganteus. Biochars were produced from two different feedstocks and at different pyrolytic conditions in order to have contrasting structure of the biochars. Biochar 1 was provided by Rees, F. (France) and biochar 2 by Fellet, G. (Italy). The biochars were provided within European project scope. Biochars were air-dried at room temperature and then sieved (>2 mm).

4.3.Preparation of experiment

The experiment was designed with contrasting biochars (applied at different application rates) in order to examine and evaluate effects on K_{sat} and WHC. The measurements were conducted on samples collected from 5 trial boxes, which contained mixture of soil and amendment. The soil was treated with biochar made from hardwood & softwood mixture, and plant feedstock.

The soil was well mixed with biochars at 1 % wt and 2 % wt ratios with 20kg of air-dried soil and equally spread and layered in a box with irrigation wicks - through which the soil amended with biochar was wetted (figure 7 and 8) - attached to tubes (volume of 15 ml) along the sides of each box, which were regularly filled with distillated water to prevent drying of the mixture. This was done in order to keep semi-constant volumetric moisture content at certain range of values. Then the boxes were compacted by hand pressure. A control box without any amendments was set in order to compare the results with samples treated with different types of biochars.

The boxes filled with a mixture of soil and biochar were left for a month in room with constant conditions, in order to achieve full saturation of soil and biochar and to get equal conditions throughout the box. During maturing of the prepared boxes the soil moisture tension was monitored with tensiometers in control box. The temperature and humidity was stable during the maturing.

The samples for K_{sat} and measurements of WHC were retrieved at the same time, after one month (figure 9) of the maturing with stainless steel rings of volume of 100 cm^3. There was around 20 steel rings retrieved from each box.

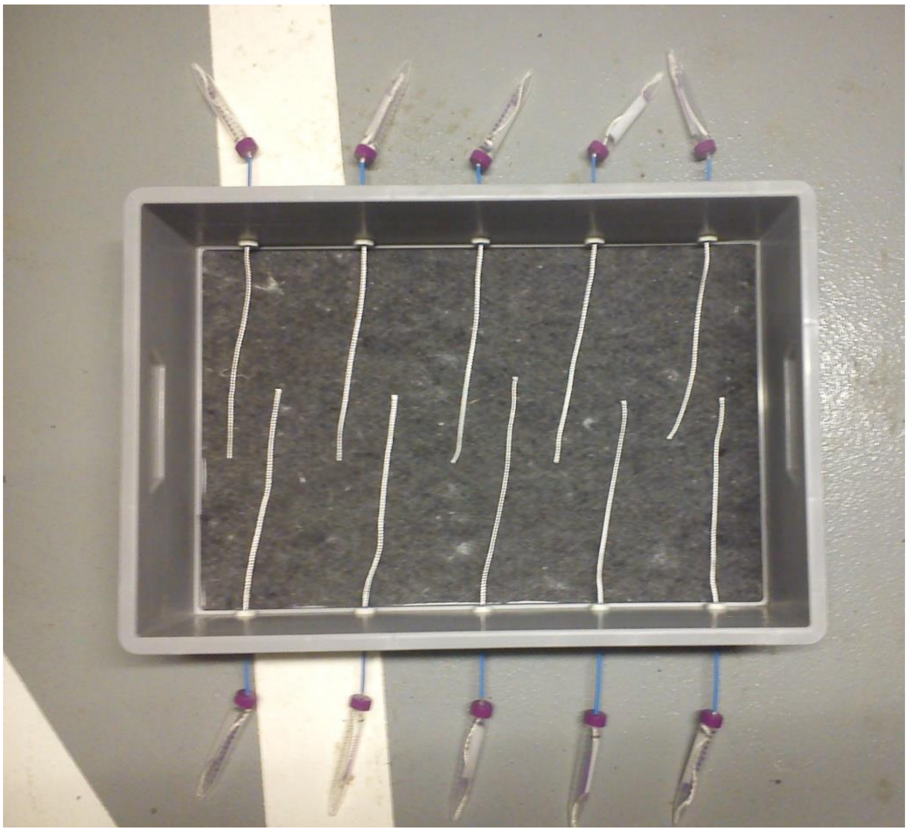

Figure 7 - A box with irrigation wicks ready to be filled with soil amended with biochar (Author's photo)

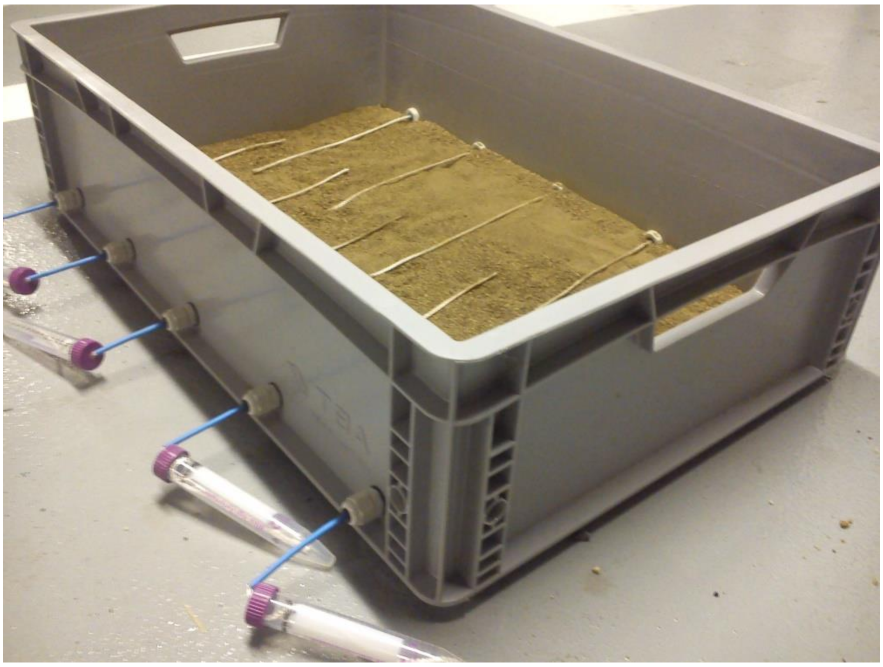

Figure 8 - Box partially filled with soil amended with biochar (Author's photo)

Figure 9 - Box filled with soil amended with biochar before collecting the samples (Author's photo)

4.4.Measuring of saturated hydraulic conductivity

K_{sat} is very sensitive to sample size and soil characteristics. Observations showed that most of its measurement methods are not accurate for all soil types and conditions (Sarki, et al., 2014). In the experiment the K_{sat} was measured by constant head method. The samples were put into the permeameter (figure 10 and 11) and gradually saturated from the bottom to the top, as it is shown in the figure 12, during overnight. Thus the air potentially trapped in pores got released.

The K_{sat} value is determined by measuring the volume of water passing through the sample at given time interval. The experiment was performed in three separated time-steps in order to get representative values of K_{sat}. The samples were measured in batches, because the permeameter can hold maximally 10 samples. Therefore the measurement of K_{sat} value of treated samples was done sequentially, where the time difference between the first and second measurements was usually few hours and the time difference between the second and third measurement was approximately one day. The time difference between the measurements is helpful because it will stabilize the sample within the steel ring and thus provide more consistent data. The dimensions of sample were recorded – the volume of the steel ring is 100 cm^3. Temperature of water was continuously measured and was relatively constant with small variations. K_{sat} values were calculated according to Darcy's equation (2):

$$K_{sat} = \frac{V_w \, L_s}{A_c \, \Delta t \, \Delta h} \qquad (2)$$

In which the V_w express the volume of water that passed through the sample during time interval Δt, L_s is the length of the steel ring, A_c is area of the soil column, Δh express the difference of the water tables inside and outside of the sample rack.

After the experiment was performed in all three time-steps the samples were weighted and then placed to an oven at constant temperature of 105 °C for 24 hours in order to dry. After drying the weight of each sample was recorded. This data was then used for calculation of basic physical characteristics of different treatments.

Figure 10 - Permeameter for measurements of saturated hydraulic conductivity (Author's photo)

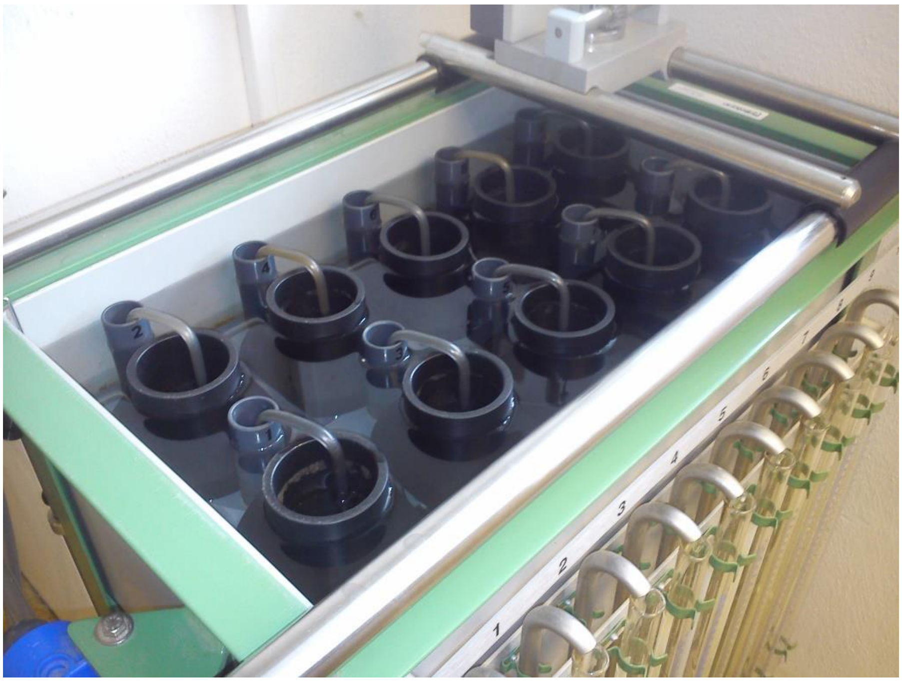

Figure 11 - Samples during measurements of saturated hydraulic conductivity in permeameter (Author's photo)

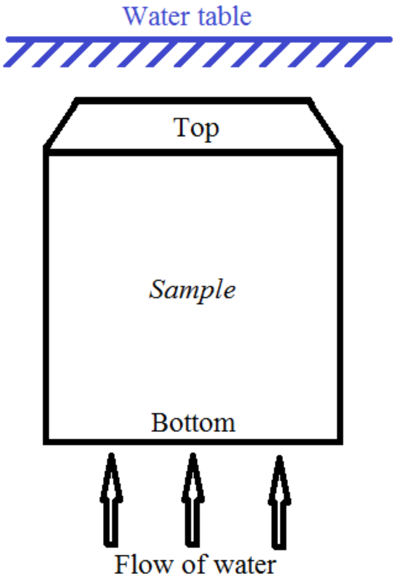

Figure 12 - Detail of the K_{sat} experiment, steel ring with sample placed in permeametr

4.5. Measuring of water holding capacity

For the measurements of WHC was chosen 16 representative samples, 3 samples from each treatment box and 4 samples from the control box. The measurements took place in sand box (which is design for low suction pressure, figure 14), sand-kaolin box (medium pressure), and on the pressure plate extractor for medium and high pressure.

In the sand box the samples were firstly saturated with water at pF 0, then the water was discharged and the water and moisture began to be drained from the samples. Every time before the pressure was increased the weight of samples was recorded. Table 2 shows the duration of drainage of samples at given pressure in different draining units.

Suction pressure head	Sand box n=3 [days]	Sand-kaoline box n=3 [days]	Pressure plate *n=2 **n=1 [days]
pF 0.00	3	---	---
pF 0.40	4	---	---
pF 1.00	3	---	---
pF 1.50	4	---	---
pF 1.80	7	---	---
pF 2.00	---	21	---
pF 2.70	---	14	---
pF 3.00	---	---	14*
pF 3.47	---	---	13*
pF 4.18	---	---	35**

Table 2- Table showing the duration of drainage under different pressure in different draining units

When the experiment finished all samples were dried in an oven at temperature of 105 °C for 24 hours. Then the weight of dried sample was recorded in order to obtain the final moisture content of each sample. All data were then used for calculation of variables needed to plot the graphs representing the moisture content at given pressure. The moisture content was calculated by the difference of weights between different pressures. The measured data were used to fit the soil water retention model of van Genuchten (1980):

$$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1+(\alpha|h|^n)^{1-1/n}\right]} \qquad (3)$$

where θ is volumetric soil water content ($cm^{-3}\ cm^{-3}$), $|h|$ is the suction (cm), θ_r and θ_s are the residual water content and saturated water content ($cm^{-3}\ cm^{-3}$) respectively, and α (per cm) and n are the fitting parameters. The resultant curve represent the amount of water at different pressures, which can be easily compared with water retention curve of other samples by visualization. Certain characteristics can be determined based on the progress and curvature of the final curve. Thus we can examine and evaluate behavior of the amendment in the soil and its effects on hydraulic properties – i.e. WHC. Apart from that, it is possible to determine the volume of water available for plants, this interval lays in between the blue lines of figure 13. The PAWC can be calculated by the difference between the field capacity (the water content at suction of 330 cm, pF 2.00) and the wilting point (the water content at suction of 15,000 cm, pF 4.18) (Saxton & Rawls, 2006). Water below the lower blue line is moving freely through the sample by gravity. The water above the upper blue line is stored in extremely small pore with diameter >2 μm.

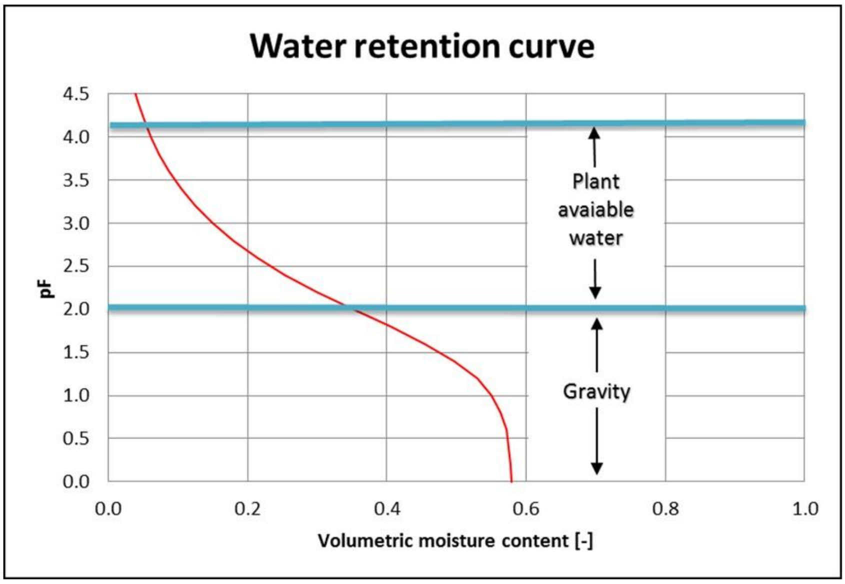

Figure 13 - Illustration of water retention curve

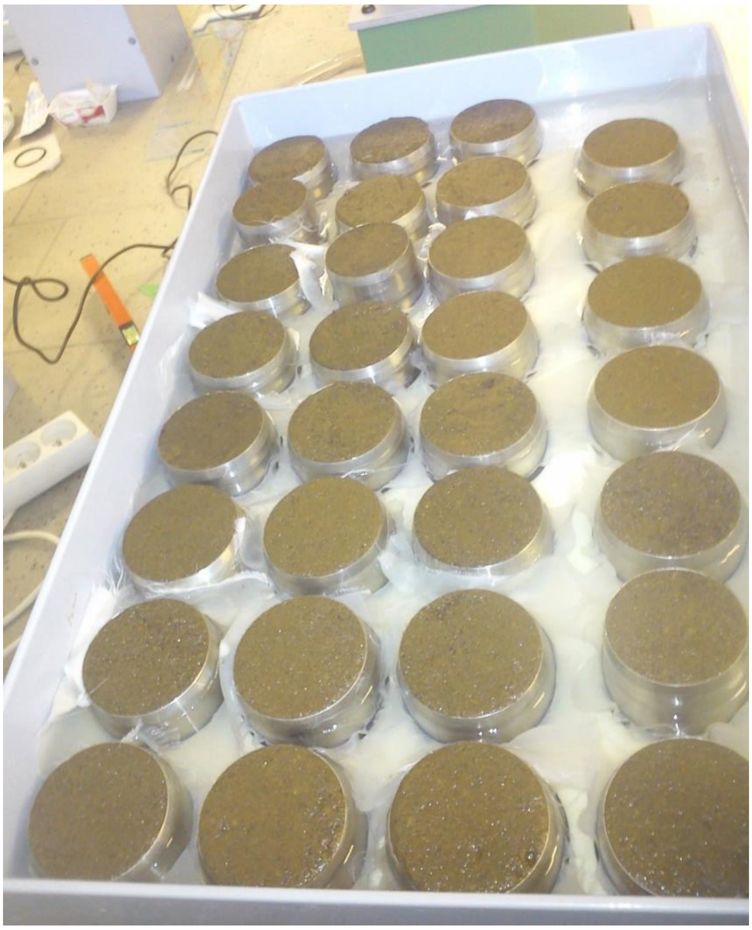

Figure 14 - Sand box for measuring the WHC (Author's photo)

4.6. Statistical analyses

All statistical analysis was done in R software environment at the 0.05 probability level. The data were check for normality using Shapiro-Wilk normality test. One-way ANOVA was carried out in order to assess differences in K_{sat} and WHC between treated samples and control samples. Tukey's test was carried out when significant effect was observed.

5. Results

Characteristics of soil

The table 3 summarize the characteristics of soil used in experiments. The content of inorganic carbon was below detection limit. There was no presence of fraction higher than 2 mm (> 2 mm). More than half of the soil was composed from sand fraction. Generally the sandy loam soil reaches the saturation point much sooner (due to its limited WHC) than soils with higher WHC (such as a clay loam).

Texture %			CEC (mmol⁺/kg)	Total carbon (%)	
Clay (<2 μm)	Silt (2-50 μm)	Sand (0.05-2 μm)		TOC	TIC
8.7 ± 1.0	34.8 ± 4.3	56.5 ± 4.4	90.8 ± 4.2	2.15 ± 0.01	<DL

Table 3 - Characteristics of used soil; data shown are means ± SD

The figure 15 shows the pore-size distribution of the soil used in the experiment. The texture was determined using hydrometer method and then classified as sandy loam (USDA textural triangle – figure 16).

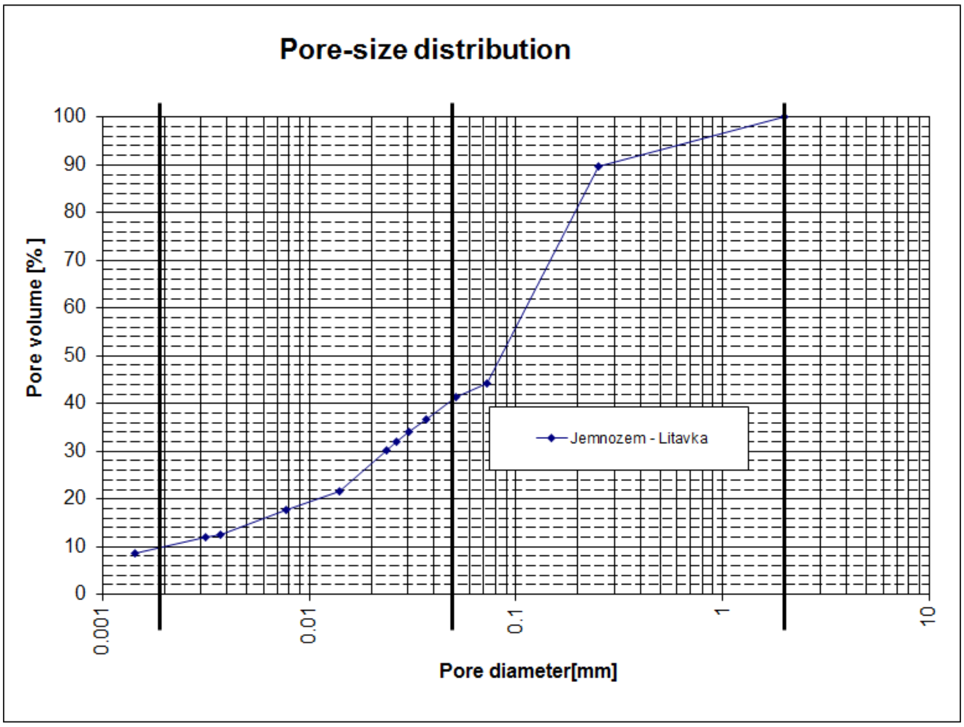

Figure 15 - Pore-size distribution of collected soil

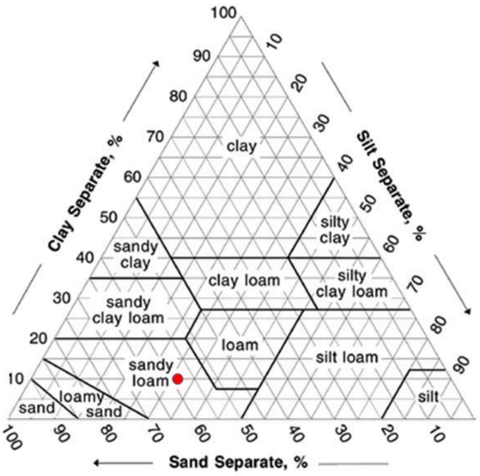

Figure 16 - Determination of type of soil according to USDA texture triangle

Characteristics of biochar

Table 4 provides characteristics of each biochar used in experiment. These data were provided by the producers and were not measured as a part of this experiment. The application rates are displayed in table 5.

	Biochar 1	Biochar 2
Provided by	Rees, F *(France)*	Fellet, G. *(Italy)*
Feedstock	50% hardwood; 50% softwood (sieving residues)	Miscanthus x giganteus
Pyrolysis temperature (°C)	650	500-550
pH in water	9.62	10.1
Electrical conductivity (mS/cm)	0.228	0.793
CEC (cmol$^+$/kg)	3.2	3.63
Organic C (g/kg)	685	784

Table 4 - Main characteristic of used biochars

Sample labeling (type of feedstock)	Application rate (%)
1BC_plant *(Miscanthus x giganteus)*	1
2BC_plant *(Miscanthus x giganteus)*	2
1BC_wood *(50% hardwood; 50% softwood (sieving residues))*	1
2BC_wood *(50% hardwood; 50% softwood (sieving residues))*	2

Table 5 - List of trials and application rates of biochar

The biochars were produced from different feedstocks at different pyrolysis temperature in order to obtain contrasting biochars for the experiment (table 4). These variables influences behavior of biochar in the soil and thus may affect the hydraulic properties. For instance, CEC is considered as indirect measure of ability of soil to hold water (Major, et al., 2009), the CEC of used biochars has not varied a lot. The pH value was more or less stable for both biochars.

Soil moisture tension

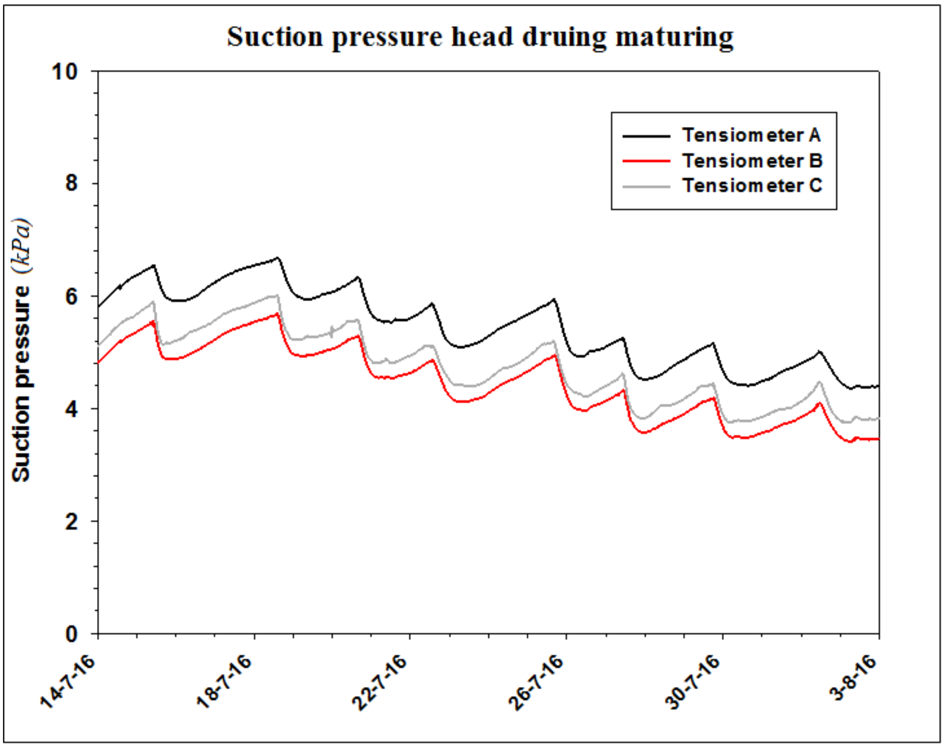

Figure 17 - Soil moisture tension measurement during maturing of the boxes

The suction pressure head was measured continuously during the maturing of control box (figure 17) in order to keep semi-constant value of moisture in the soil. It expresses the force, which plants must overcome, in order to obtain water from soil. This force also determines distribution of soil moisture and transport of moisture within the soil. The pressure head during maturing ranged from -6.7 to -3.4 kPa, so the content of moisture during maturing corresponds to approximately 74 % of WHC of given soil.

5.1.Saturated hydraulic conductivity

Table 6 describe physical properties of samples used for the K_{sat} experiment. The different number of samples of each treatment is caused by errors occurred during the experiment. The volume of moisture was calculated by the difference of weight of sample (recorded when it had been retrieved from box) and dried sample. The highest volume of moisture (at the time of collection of samples) had the samples treated with 1 % application of woody biochar, namely 38.90 %, whereas the lowest volume of moisture out of the treated samples had samples treated with plant biochar at 2 % application rate, respectively 33.42 %, which is not does not corresponds to what was expected. The plant biochar applied at 2 wt % had even lower value of moisture content than control samples, respectively 33.42 % and 36.53 %. The BD of wood biochars has the highest values, although the biochar should decrease the BD of soil. On the other hand, the BD of samples treated with plant biochar was lower than the BD of control sample, respectively 1.02 and 1.09. All measured values are displayed in table 6.

	Average values & SD		
Treatment	Volume of moisture [%]	Porosity [-]	Bulk density [g/cm^3]
1BC_plant*	37.68 ± 2.16	0.61 ± 0.01	1.02 ± 0.03
2BC_plant**	33.42 ± 2.10	0.61 ± 0.02	1.02 ± 0.04
1BC_wood***	38.90 ± 4.21	0.57 ± 0.01	1.14 ± 0.04
2BC_wood$^{\times}$	38.44 ± 0.77	0.57 ± 0.01	1.14 ± 0.03
Control$^{\times\times}$	36.53 ± 3.13	0.59 ± 0.01	1.09 ± 0.03

*n=2 **n=9 ***n=5 $^{\times}$n=8 $^{\times\times}$n=7

Table 6 - Physical properties of samples used for K_{sat} experiment

The K_{sat} values from the 1st and 2nd time-step did not showed any statistically significant differences in measured values, although the 1BC_plant *p value* were 0.051 and 0.055 compared to the control sample for the 1st and 2nd time.step (figure 20 and 21). The 3rd time-step – plotted in figure 18 – showed a statistically significant difference in K_{sat} values between 1BC_plant and control treatment, respectively *p value*=0.037.

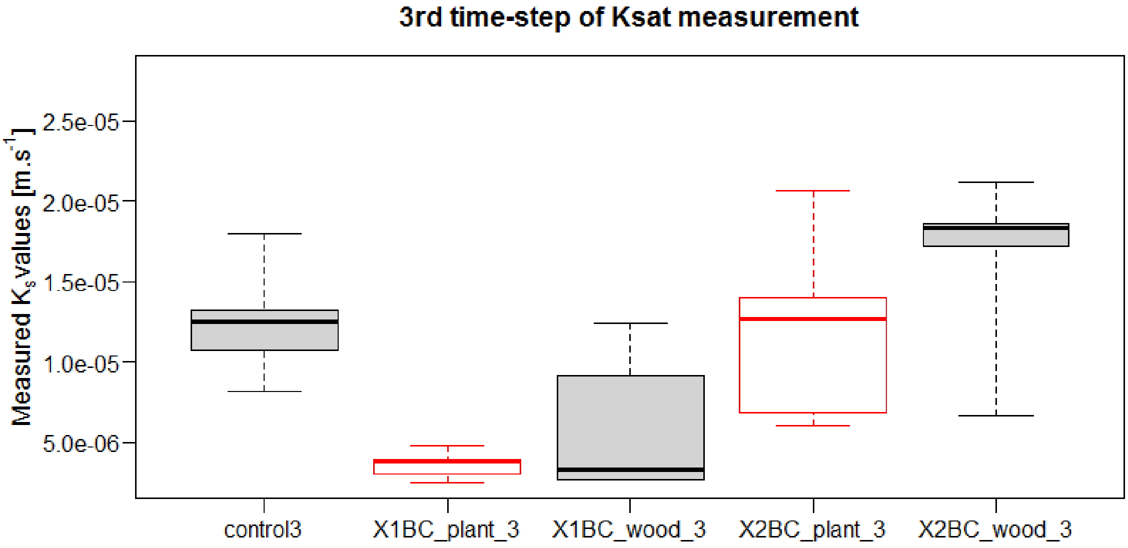

Figure 18 - K_{sat} values of treated samples vs the control sample at 3rd time-step

The table 7 provides overview of average values and its standard deviations. In the 1st time-step all samples treated with biochar affected K_{sat} values, where the 1 % application rate had biggest impact on the K_{sat} values, the control samples had the highest values. In the 2nd and 3rd time-step the highest K_{sat} values were measured for 2BC_wood. The 2 % application rate showed to be not that effective, the K_{sat} value was increased with comparison to the 1 % application rate.

	Average + SD [m/s]		
Treatment	1st time-step	2nd time-step	3rd time-step
1BC_plant	5.16E-06 ± 1.08E-06	3.95E-06 ± 9.74E-07	3.61E-06 ± 8.78E-07
2BC_plant	1.07E-05 ± 5.46E-06	1.17E-05 ± 8.35E-06	1.20E-05 ± 5.93E-06
1BC_wood	8.35E-06 ± 6.79E-06	6.21E-06 ± 4.65E-06	6.06E-05 ± 4.47E-06
2BC_wood	1.48E-05 ± 4.22E-06	1.51E-05 ± 5.67E-06	1.64E-05 ± 5.63E-06
control	1.55E-05 ± 7.39E-06	1.42E-05 ± 5.17E-06	1.25E-05 ± 3.63E-06

Table 7 - Average K_{sat} values for all measured samples sorted by the highest K_{sat} values to the lowest values for each time-step

5.2. Water holding capacity

Table 8 provides physical characteristics of samples used for measuring RETC. The volume of moisture was calculated by the difference of weight of sample (recorded when it had been retrieved from box) and dried sample. The volume of moisture varied a lot namely for the 2BC_plant and 1BC_plant, which showed to have the smallest content of moisture when the samples were collected. Surprisingly, only 1BC_plant and 2BC_plant had smaller bulk density than the control samples, despite the fact that biochar is supposed to decrease the bulk density of soil. However, the differences of BD of the treated samples and control samples did not show to be statistically significant. The same trend was observed among samples used for K_{sat} experiment. The differences in volumetric moisture (measured when the samples were collected) were not statistically significant between treated samples and control samples.

	Bulk density [g/cm^3]	Volume of Moisture [%]	Porosity [-]
Treatment	Avg. & SD	Avg. & SD	Avg. & SD
1BC_plant	1.00 ± 0.09	38.41 ± 3.29	0.62 ± 0.04
2BC_plant	0.99 ± 0.07	34.19 ± 2.23	0.62 ± 0.03
1BC_wood	1.16 ± 0.02	42.45 ± 1.07	0.56 ± 0.01
2BC_wood	1.16 ± 0.01	39.36 ± 0.82	0.56 ± 0.01
control*	1.09 ± 0.04	39.02 ± 1.29	0.59 ± 0.01

n=3

Table 8 - Basic physical characteristics of samples used for RETC

Table 9 provides overview of measured volumetric moisture content for each treatment at given suction pressure and the PAWC. The biochar application increased the PAWC in all cases. The effects of biochar on WHC, based on comparison of PAWC, was more obvious for 1BC_plant and 2BC_plant. The volumetric moisture content at suction pF 0 was increased only for 1BC_plant, 2BC_plant, other samples evince the opposite effect compared to control samples. The measured volumetric water content at low suction pressures (up to pF 1.0 – table 10) followed trend, where the 1BC_wood and 2BC_wood had lower WHC than the control samples and 1BC_plant and 2BC_plant had higher WHC. The sample treated with 1 % application of plant biochar (1BC_plant) had the highest volumetric moisture content at wilting point (pF 4.18).

Treatment	pF 0	pF 1.5	pF 2.7	pF 3.47*	pF 4.18**	PAWC
	Avg. & SD	Avg. & SD	Avg. & SD	Avg. & SD	Avg.	
control	54.37 ± 1.13	51.37 ± 1.06	21.07 ± 0.32	14.73 ± 0.08	9.97	23.42
1BC_wood	52.02 ± 1.33	49.31 ± 1.65	20.00 ± 0.89	12.97 ± 0.95	8.86	24.04
2BC_wood	50.77 ± 0.68	47.79 ± 0.17	20.50 ± 0.69	12.94 ± 0.25	8.93	24.22
1BC_plant	55.46 ± 3.07	51.25 ± 0.83	22.82 ± 0.42	15.09 ± 0.62	10.56	26.02
2BC_plant	55.05 ± 3.55	51.55 ± 1.48	23.01 ± 0.27	15.24 ± 0.44	10.49	24.99

n=3 *n=2 **n=1

Table 9 – Volumetric moisture content at given suction pressure for all treated samples and PAWC

Figure 19 shows comparison of retention curves of 1BC_plant and control samples and SD. The observed effect of biochar is positive, it favorably affects the WHC. The PAWC was increased by the application of biochar. However, it is important to note, that the van Genuchten model did not fit the data exactly as were measured, especially in high suction pressure the van Genuchtel model seemed not to work appropriately – i.e. in some cases the measured samples had the actual volumetric moisture content higher than was plotted by van Genuchten fitting model, this can be seen in figure 19. Therefore the measured values in table 10 are more representative in meaning of the actual behavior of given biochar in soil. The figure 22, 23, and 24 shows retention curves of other treated samples.

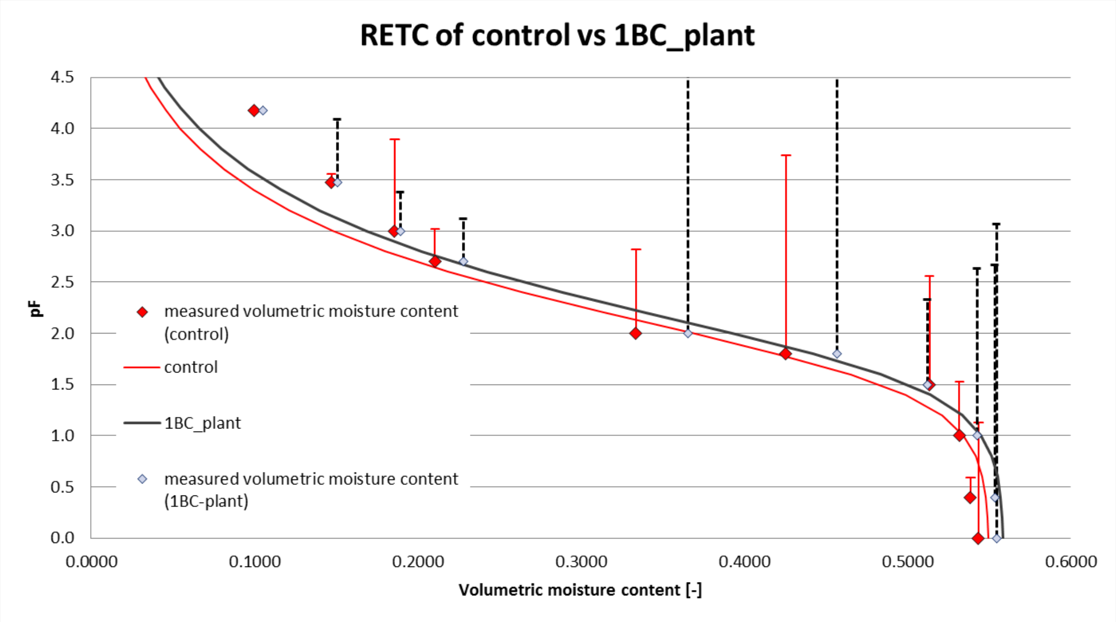

Figure 19 - RETC of 1BC_plant vs control samples with SD

6. Discussion

As was mentioned, results of the performed experiments were influenced by the setting conditions, where in the initial stage of experiment, the factor of compression was neglected. Another point is that the experiments were conducted on samples retrieved from repacked soil box, this could influence the results as well. In general the hydraulic properties varied a lot between biochars, this might be attributed also to the internal and external porosity, particle size, and surface tension, which under different conditions can make biochar either hydrophilic or hydrophobic (Allaire, et al., 2015). Author of the thesis assumes that those factors contributed to the development of swelling effect, which was observed during the maturing of mixed soil, thus the volume increased. This had a major impact on the results. This error was expected. The experiments showed that the application of biochar slightly improved the K_{sat} and PAWC was increased.

Physical properties of amended soil

The BD of soil decreased only for samples treated with biochar derived from plant, respectively 1BC_plant and 2BC_plant. This is in consistence with finding of Głąb et al. (2016), who used biochar derived from same feedstock (Miscanthus x giganteus), however, in their case the BD values were reduced with increasing application rate. Zhang et al. (2010) observed similar effect with application of plant derived biochar (wheat straw biochar), which decreased the BD of rice paddy soil at application rate equal to 40 Mg ha^{-1}, however, this effect was not observed at application rate of equal to 10 Mg ha^{-1}. Findings of other authors with regards to wood based biochar application are rather opposite to what was found out in this thesis. The reduction of BD of soils amended with woody biochars is reported in many peer review literature, for instance Major et al. (2012) reported application rate equal to 20 Mg ha^{-1} of wood based biochar significantly reduced BD of a heavy clay soil, however this could be observed only at depth of 0-15 cm, but not at the soil surface nor at 0.15-0.30 cm depth. Hardie et al. (2014) observed significant reduction of soil BD when wood based biochar was applied at application rate equal to 47 Mg ha^{-1}. Chen et al. (2011) results showed that application at application rate equal to 2.3 Mg ha^{-1} and 4.5 Mg ha^{-1} decreased the bulk density by 4.5 and 6.0 %. These findings are opposite to the results of this study, where the wood based biochar unexpectedly increased the BD of treated soil (1BC_wood, 2BC_wood) compared to control sample.

The total porosity was increased only for plant derived biochar (1BC_plant and 2BC_plant), which corresponds to findings of Głąb et al. (2016). Contrary to the observations of other authors, the total porosity of wood based biochar increased with respect to the untreated samples. Hardie et al. (2014) described decrease of total porosity of soil amended with acacia based biochar and suggested that this resulted from the creation of large macropores in the soil surrounding the biochar particles.

Saturated hydraulic conductivity

The K_{sat} experiment performed in this study, resulted in decrease of the K_{sat} so the application of biochar led to slightly improvement of soil hydraulic conductivity (except the samples treated at 2 % application rate with woody biochar). The only statistically significant difference between treatment samples and control sample was the 1BC_plant at 3rd time-step. The samples with 2 % application rate of biochar had surprisingly higher K_{sat} values than the samples with 1 % application rate and in case of 2BC_wood the median value was even higher than for the control sample. This was attributed to swelling effect, which caused that the amended soil in boxes increased its volume as it swelled. This could led to forming of preferential pathways through which the water can more easily flow, thus we can observe higher K_{sat} values than for the control sample. This also points to differences of K_{sat} values between soil samples amended with biochar at different application rates.

Important is to note, that with increasing application rate of biochar, the K_{sat} increased. The same results obtained Jirků et al. (2013), where in their study the addition of biochar led to soil aggregation, which resulted in an increase of the macropores, thus the K_{sat} was increased as well.

Liard et al. (2010) did not find any significant influence of hardwood biochar on K_{sat} in their experiment. Major et al. (2012) obtained similar results in their *in situ* experiment, where wood biochar was applied at application rate equal to 20 t ha^{-1}, however, no significant differences were observed for the K_{sat} between soil with and without biochar. Ibrahim et al. (2013) have observed decrease of K_{sat} after the application of biochar to soil. Similar conclusions we made by Uzoma et al. (2011) and Asai et al. (2009) who observed improvement of K_{sat} in biochar amended soil. Asai et al. (2009) showed that application of wood-residue biochar at application rate equal to 4 Mg ha^{-1} and 8 Mg ha^{-1} did not significantly affect the saturated hydraulic conductivity, although at application rate equal to 16 Mg ha^{-1} a significant difference existed at one of two sites, particularly on site with soil having only 28 % of clay with contrast to the other site, where the soil had 48 % of clay.

Contrary to those findings are the observations of Lei and Zhang (2013), who's experiment resulted in increased K_{sat} in soil amended with biochar, in their case it were two types of biochars, namely woodchip biochar and manure biochar mixed at 5 wt %, where the K_{sat} of woodchip biochar was higher than K_{sat} of manure biochar. The authors attributed this effect to more macropores formed in woodchip biochar and concluded, that the biochar application increased K_{sat}, and this effect increased with increasing biochar pyrolytic temperature. Also the biochars which were used in their experiment had relatively high ash content. With regards to the ash content Verheijen et al. (2009) described the possibility of change of electrical charges on clay particles, by the ash fraction, which causes the soil particles to move closer, thus increase secondary macroporosity, and as a result it could led to increase of K_{sat}. Lei and Zhang (2013) concluded that the K_{sat} values were not significantly different. Findings of Lei and Zhangs (2013) are supported by Ajyai et al. (2016) results, where the increasing application rate of hardwood biochar, from 5 to 10 % respectively, to sandy soil led to reduction of K_{sat}, while at 2 % application rate the K_{sat} was not significantly reduced. At the same time Ajayi et al. (2016) observed that in the finer textured sandy loam silt, the K_{sat} was slightly increased.

Kameyama et al. (2012) reported increased K_{sat} at higher application rates of biochar made from sugarcane bagasse, but at application rates of 3 wt % and below the authors did not find such effect.

Water holding capacity

In the WHC experiment of this thesis the woody biochars evidenced that the PAWC increases with biochar application rate (1BC_wood, 2BC_wood – table 9), which corresponds to findings of de Melo Carvalho et al. (2014) who did the experiments on sandy loam soil with 1.5 wt %. However, in the WHC experiment performed in this thesis, the increment of PAWC between 1 % and 2 % application rate was very low. The increase of volumetric moisture content was observed also between 1BC_plant and 2BC_plant at given suction pressures, namely 1.0, 1.5, 2.7, 3.0, 3.47 (table 10).

Unlike the results obtained in this thesis, are findings of Burrell et al. (2016) and Ojeda et al. (2015). Ojeda et al. (2015) results showed that the potential plant uptake was not modified by biochar amendments. Burrell et al. (2016) have not found any effect of wood biochar on PAWC. Those results are supported by Major et al. (2012) report, where the use of woody biochar *in situ* did not have any significant effect on moisture retention at the surface, 0.15 and 0.3 m depths. Hardie et al. (2014) reported no significant effect of *in situ* application of acacia green waste biochar on PAWC between – 10 kPa and -1500 kPa of suction pressure. Gaskin et al. (2007) found that application of pine-chip biochar had no significant effect on the soil water holding capacity of a loamy sand soil at application rate equal to 11 and 22 Mg ha^{-1}, however, a significant differences occurred at application rate equal to 88 Mg ha^{-1}. Nevertheless, the economic viability is disputable at such high application rates. Gaskin et al. (2007) concluded that low application rates of biochars do not appear to increase the WHC of loamy sand soils and noted that the obtained data indicates much higher application rates are necessary to significantly alter water relations in this type of soils.

Findings of Abel et al. (2013) and Ulyett et al. (2014) are contrary to the results obtained from WHC experiment of this thesis, where at the highest matric potential the woody biochar, respectively 1BC_wood and 2BC_wood, had lower content of volumetric moisutre than the control sample. Findings of these two research groups showed that the soil amended with woodchip biochar held more water at permanent wilting point (pF 4.18), due to the higher specific surface area which increased the ability to hold more water at higher matric potentials. With respect to the biochar derived from plant, the results of this thesis are in coherence with observations of

Burrell et al. (2016) where they found positive effect of straw biochar on PAWC in Planosols, and no effect of specific surface area of woodchip biochar could be observed, although the specific surface area was higher than the one of straw biochar. Concerning the woody and plant derived biochars, Abel et al. (2013) reports a 35 % increment in PAWC in loamy sand soil by use of beech wood biochar with particle size < 5000 µm. However, according to Sochi et al. (2010), this additional water may not be readily available, because the water is too tightly held, in the very small saturated pores, against the plant's uptake forces. On the contrary to the observations of author of thesis, Dempster et al. (2012) observed big increment (by 71 and 127 %) of soil water content at low matric potentials (up to -1500 kPa) in sandy soil with application of wood biochar. Lei and Zhang (2013) study showed that biochar application significantly influenced RETC, where the WHC is directly affected by biochar application, the WHC is related to the larger inner surface area of biochar, the indirect effect is same as for K_{sat}, which is described in the chapter above, namely the soil aggregation (Verheijen, et al., 2010). This is in contrast of Mohamed et al. (2016) report, where no significant difference was found between WHC of samples. The proposed reason for decrease of WHC with increasing biochar application rates for some soil samples (with added biochars) could be linked to the hydrophobic nature of used biochar, causing water repellency, and thus decrease of soil WHC. This concerns biochar which showed a significant decline in WHC after the biochar application rate was increase from 1 to 2 wt %. Głąb et al. (2016) in their literature review described that biochar can promote water repellency and counteract the potential positive effect on the WHC, where the repellency of water may contributing to higher volume of entrapped air followed by decrease of the fraction of saturated pores, which leads to reduced PAWC and hydraulic conductivity. This was probably one of the main factors in case of the experiments conducted in this thesis.

Other researchers are reporting opposite effect, for instance Lei and Zhang (2013) in their study used woodchip biochar produced at 300, 500 and 700°C, applied to soil at application rate of 5 %. The soil water content increased by 39, 51 and 55 % in sandy loam soil. The results of de Melo Carvalho et al. (2014) showed a 4, 13, and 26 % increment in PAWC. The increase of soil water content with an increase in the quantity of added biochar is supported by findings of Ibrahim et al. (2013). Novak et al. (2009) study resulted in significant differences of WHC between different types of biochars. Results of Basso et al. (2013) showed a big increase in water content when red oak biochar (produced at high pyrolysis) was used at application of 3 and 6 wt %, however it is a question if such high application rates are economically feasible and viable. Ajayi et al. (2016) observed enhancement of moisture retention when sandy and silty substrates were treated with woody biochar. Furthermore, the increasing application rate increased the WHC of both types of soils.

Lei and Zhang (2013) observed higher water content values of treatments with biochars produced at high pyrolysis temperatures at given suction pressure, which is in contrary to the data obtained from the WHC experiments of this thesis. In this thesis

WHC experiment, the highest WHC, among the 1 % application rate treatments (in means of PAWC), had the plant biochar. Wang et al. (2015) observations showed only a slightly better water holding ability of grass biochars than the wood biochars.

7. Conclusion

The results of both experiments, the K_{sat} and the WHC, in some way confirmed what was hypothesized. However, the measurements are strongly influenced by the setting of the experiment, the setting conditions are fundamental. Experiments described in this thesis were influenced by the factor of consolidation, where the soil amended with biochar, was not compressed at the surface during its maturing, and thus the swelling effect fully developed.

In both experiments the BD of soil amended with plant biochar compared to the control samples decreased, while the BD of soil amended with wood biochar increased.

K_{sat} experiment showed that there was statistically significant difference in the K_{sat} value in 3rd time-step between 1BC_plant and control sample. On the other hand, the 2 wt % application rate showed undesired effect on K_{sat}, where it increased the K_{sat} value. This was probably caused by the swelling of biochar, which consequently created preferential pathways through which the water could flow with ease. The volumetric moisture content of treated samples (calculated when the samples were collected) was higher than the one of control samples.

The results obtained from the RETC experiment showed that the soil amended with biochar hold hygroscopic water, thus it simulates clay and as a results holds more water. All treated samples had higher PAWC than the untreated soil sample. However, the content of volumetric moisture throughout the experiment had some variations.

Unfortunately, with respect to the volume of measured data for K_{sat} and the RETC, the other two characteristics of biochar, the dissolved organic carbon leaching and biochar stability in soil, which were part of this thesis experiments, could not be measured and assessed.

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9. Appendix

Treatment	pF 0	pF 0.4	pF 1.0	pF 1.5	pF 1.8	pF 2.0	pF 2.7	pF 3.0	pF 3.47*	pF 4.18**	PAWC
	Avg. & SD	Avg. & SD	Avg. & SD	Avg. & SD	Avg. & SD	Avg. & SD	Avg. & SD	Avg. & SD	Avg. & SD	Avg.	
control	54.37 ± 1.13	53.88 ± 0.19	53.20 ± 0.53	51.37 ± 1.06	42.58 ± 1.94	33.39 ± 0.82	21.07 ± 0.32	18.61 ± 0.89	14.73 ± 0.08	9.97	23.42
1BC_wood	52.02 ± 1.33	51.52 ± 1.98	50.92 ± 1.75	49.31 ± 1.65	49.31 ± 1.65	32.90 ± 0.59	20.00 ± 0.89	16.67 ± 1.76	12.97 ± 0.95	8.86	24.04
2BC_wood	50.77 ± 0.68	50.14 ± 0.31	49.51 ± 0.34	47.79 ± 0.17	41.65 ± 0.59	33.15 ± 0.63	20.50 ± 0.69	16.33 ± 0.23	12.94 ± 0.25	8.93	24.22
1BC_plant	55.46 ± 3.07	55.37 ± 2.27	54.28 ± 1.63	51.25 ± 0.83	45.70 ± 4.90	36.58 ± 2.62	22.82 ± 0.42	18.97 ± 0.38	15.09 ± 0.62	10.56	26.02
2BC_plant	55.05 ± 3.55	55.29 ± 3.27	53.83 ± 3.21	51.55 ± 1.48	45.85 ± 2.08	35.48 ± 1.29	23.01 ± 0.27	19.31 ± 0.49	15.24 ± 0.44	10.49	24.99
n=3	*n=2	**n=1									

Table 10 - Measure volumetric content at all suction pressures

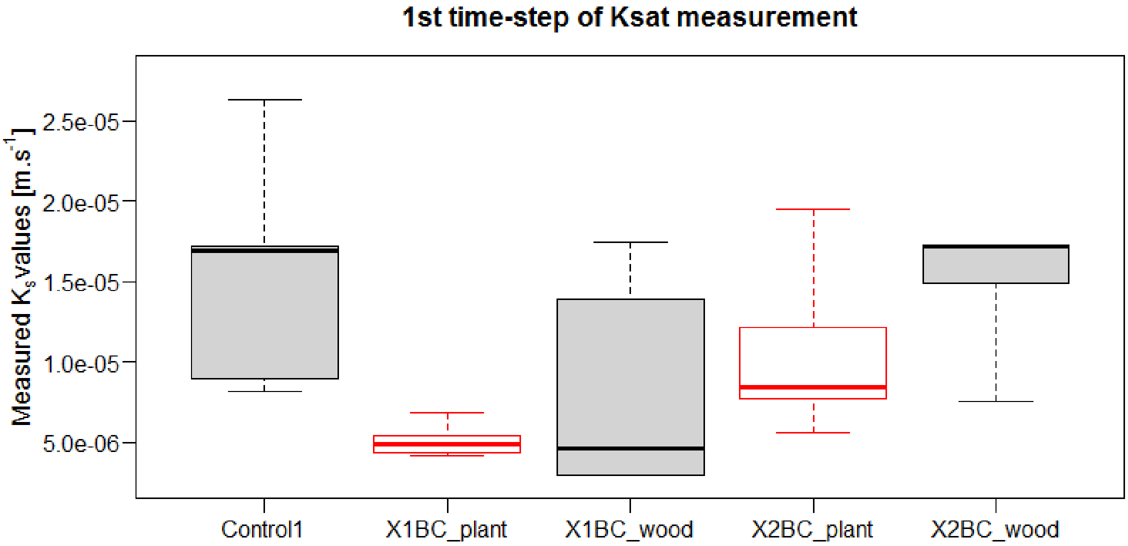

Figure 20 - K_{sat} values of treated samples vs the control sample at 1st time-step

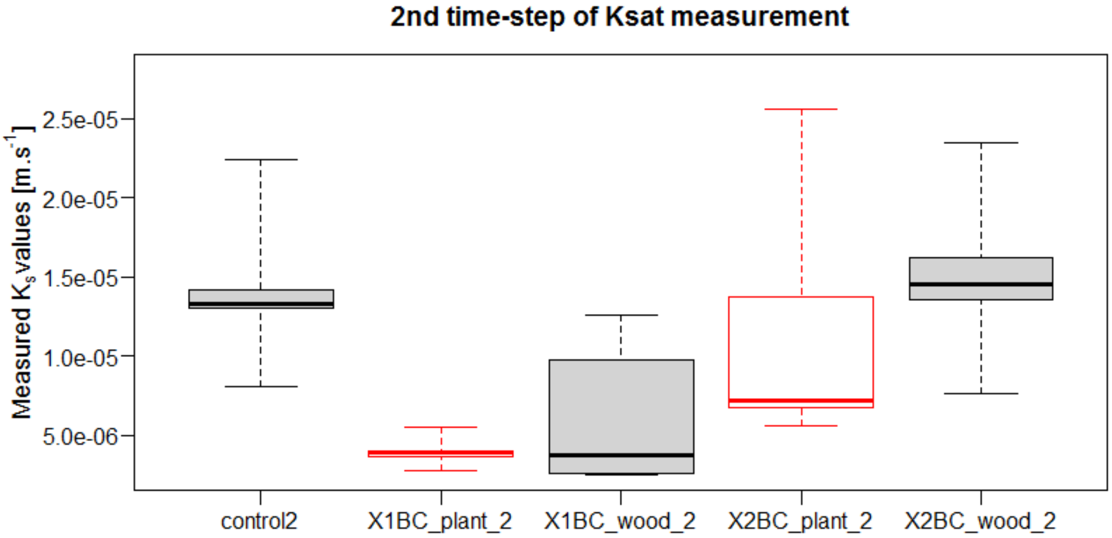

Figure 21 - K_{sat} values of treated samples vs the control sample at 2nd time-step

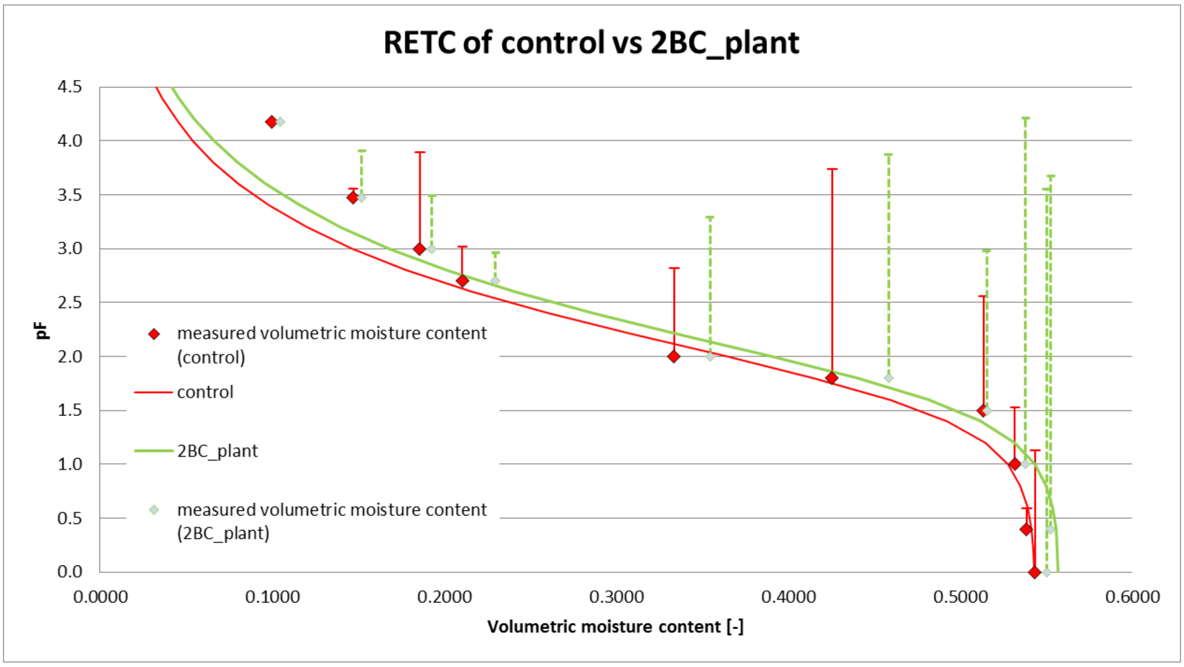

Figure 22 - RETC of 2BC_plant vs control samples with SD

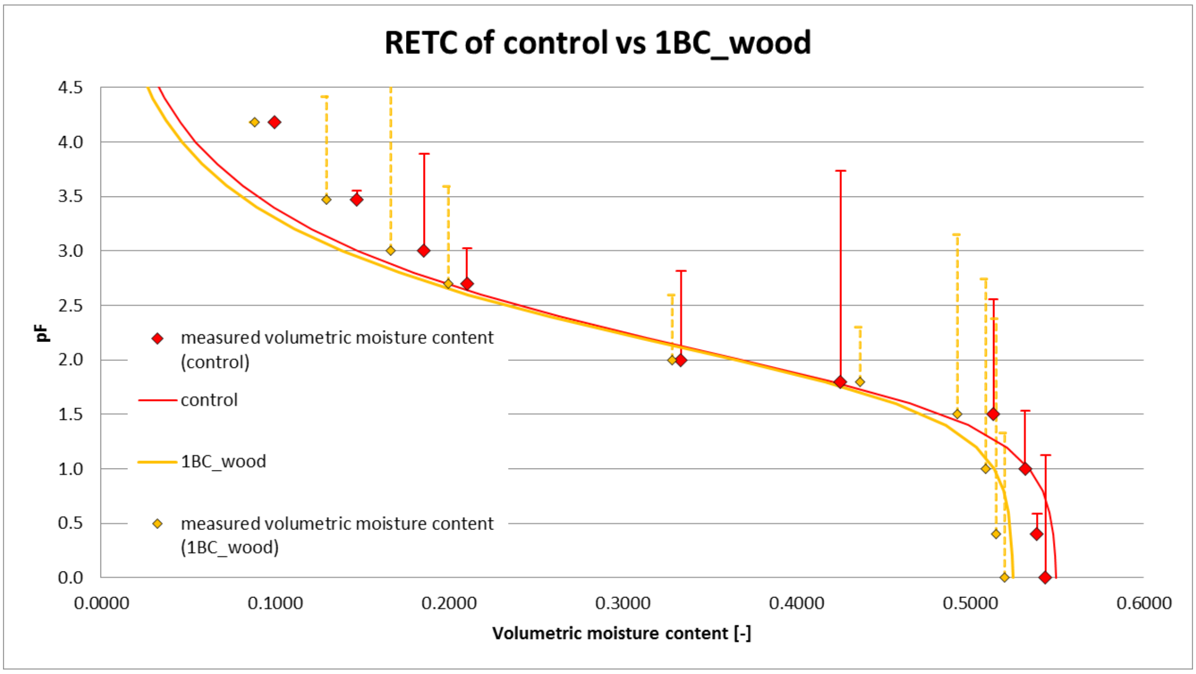

Figure 23 - RETC of 1BC_wood vs control samples with SD

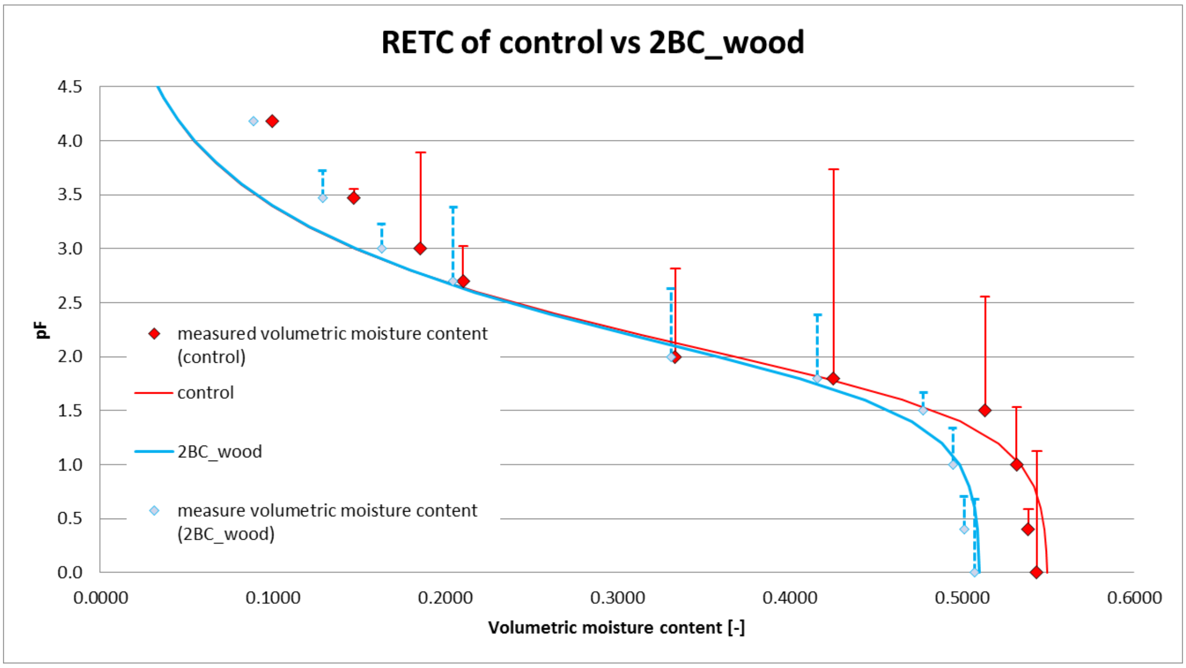

Figure 24 - RETC of 2BC_wood vs control samples with SD