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The effect of biochar admixture on the saturated hydraulic conductivity of several soils

DIPLOMA THESIS

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Declaration

I hereby declare that this Master's Thesis titled "The effect of biochar admixture on the saturated hydraulic conductivity of several soils" is my own work completed with the expert guidance of my thesis supervisor and consultant and all the sources have been cited and acknowledged by means of complete references. As an author of the thesis I declare that, in association with writing it, I did not infringe copyrights of third persons.

Prague, March 31, 2017

Signature: . . . .

Adam Dziadula

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SUMMARY

Biochar is an organic, carbon-rich material that has proven its potential for soil quality enhancement by practical applications. The aim of this thesis was to examine the ability of biochar admixture to stimulate the saturated hydraulic conductivity (K_s) of several soil types from the Czech Republic.

Disturbed soil samples were collected, homogenized, and treated with different concentrations of biochar to observe its effect on K_s on each soil type using the 250 cm^3 repacked soil samples carried out under controlled laboratory conditions on a falling head permeameter. The chosen soils for this experiment were; (1) a standard fine silica sand, (2) a light cambisol, (3) a silty-loam chernozem, and (4) a clay-loam luvisol. All of these soil types vary in physical and other soil properties. The biochar treatments applied to the samples were as follows; (1) no biochar admixture (control), (2) addition of 0.001 g/g, and (3) 0.01 g/g of biochar, corresponding to application rates of 3 t/ha and 30 t/ha respectively. Each level of treatment was carried out in three replicates. The samples were measured immediately after repacking.

The various physical properties of soils reflect the specific properties of biochar itself. By testing its influence on homogenized soil samples under distinct conditions a clear relationship was drawn not only between biochar concentration and its influence on hydraulic properties, but how the achieved hydraulic properties were correlated with bulk density and porosity. Once these relationships were defined, a clear trend of biochar mechanisms was observed. The results showed statistically significant decrease of K_s in case of light soils (from 77 to 32 cm/d in cambisol and from 743 to 524 cm/d in sand) and increase in the case of heavier soils. The rising biochar concentrations increased the K_s value of the chernozem (from 182 cm/d to 182 and then to 245 cm/d), but did not differ significantly for either of the light soils.

Keywords: biochar, saturated hydraulic conductivity, bulk density, homogenized soil sample, falling head permeameter

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1 Introduction

Biochar is a by-product of organic waste materials subdued to a low-oxygen burning process known pyrolysis. Similar to the way charcoal is produced from wood, biochar production is fueled by different feedstocks, organic agricultural wastes such as grasses, left over crop stalks, biomass, etc. It has long been known for its ability to enhance soil fertility, sequester carbon, and slow the process of global warming.

In the face of changing climate and advance of industrialization many new environmental challenges have evolved and placed heavy burdens on modern agricultural life, irrigation planning, and availability of freshwater resources. In terms of soils and suitable agricultural lands many regions of the world suffer from depletion of nutrients, dry and exhausted soils, and contamination by risk elements.

Creating solutions to modern problems of agriculture, ecology, and irrigation issues rely on establishing a sound knowledge of soil and water relationships. This includes the study of varying soil characteristics that affect water retention and conductivity, nutrient transport and solubility, organic matter, and microbial life. The application and study of biochar products has repeatedly provided evidence of soil-enhancing properties, sustainable production and carbon sequestering, and potential to reduce harmful pollutants and balance pH levels across numerous soil types, climates, and field conditions.

Improving the soil health is crucial topic in the world facing the climate change and growing human population. Using biochar to the purpose of soil enhancement and carbon sequestration as a crucial environmental topic is a big challenge. Today, very little biochar is applied to the soils for several reasons, i.e. high price of biochar for farmers without guaranteed effect on crop yields, because the mechanisms by which the soil conditions are improved are still poorly understood. Thus research must be continuously carried out in order to describe and quantify various effects of biochar to the soil (Lone et al., 2015).

2 Scientific hypothesis & objectives of work

Objectives of thesis:

To study the influence of various concentrations of biochar admixtures on the saturated hydraulic conductivity of several typical soils. The study will be carried out in the laboratory on repacked soil core samples with specific attention to the dry bulk density of the soil. Maintaining constant soil porosity will reduce the natural soil heterogeneity and thus allow for the investigation of the effects of various biochar admixtures on soil.

Hypothesis:

The application of biochar will enhance the infiltration capacity and thus affect saturated hydraulic conductivity of soils. It is projected that the application of greater biochar concentrations will increase the effect on soil hydraulic conductivity.

3 Literature Review

3.1 Basic Properties of Biochar and History of Use in Agriculture

To better define terra preta, it is an anthropogenic, or manmade soil with a high content of microbiological activity and beneficial nutrients like nitrogen, phosphorus, potassium, and calcium. It differs from charcoal in the way that it is made, through slow pyrolysis. The high nutrient and organic carbon content stored within the char helps replenish exhausted or infertile soils and develop soil that retains moisture content, a property that is beneficial for aiding environments suffering long period droughts; and fosters the growth of mycorrhizzal fungi, a soil microbe that is essential for nutrient absorption and prevention of nutrient leaching, thus confining the agricultural pollution from leaching into surrounding environments. Additionally, for modern day purposes, the production of biochar through pyrolysis yields byproducts including syngas, methane, tar, organic acid, and heat, all of which are excellent energy sources for biofuels.

As a testament to the potency and stability of biochar as a resource for enhancing agricultural cycles one needs only compare the climate and poor predisposition of the Amazon Basin for farming practices with the success of a thriving agricultural society that implemented the practice of producing *terra preta* for thousands of years. The Anthrosols created by pyrolysis many hundreds of years ago still maintain the potential to adsorb nutrients and prevent leaching. Research on the Amazon Basin's Terra Preta soils and naturally occurring biochar from forest and grassland fires implies that biochar can persist for millennia without decaying. Laboratory studies (Cheng et al., 2008, Liang et al., 2008) using the latest technology, estimate that biochar has a mean residence time in soils on the order of 1300-4000 years. But this often depends on the soil type and organic matter content.

Generally speaking, the Ferrasols, or undisturbed, naturally occurring soils of the Amazon Basin provide poor conditions for agriculture. The soil is thin, infertile, and humid, with little nutrients available at the ground surface level for plant roots to take up (van Wambeke, 1992). These conditions archeologist believe, could never have supported such the heavily populated society present in this region. Carbon rich Anthrosols had to be the fundamental element that made feeding large groups of people possible. Amazonian natives dug large pits in the ground where they threw their agricultural wastes, food residues, other organic materials, and broken clay pottery, and set them on fire. By laying the soil back over the pit, a high temperature, low oxygen environment was created preventing the carbon from oxidizing and entering the atmosphere as carbon dioxide and instead remaining trapped in the soil. This newly made biochar contained important properties, which sustain the needs of plants to thrive including oxygen, water, and a large amount of microorganisms.

Biochar has a very porous structure, enabling the unrestricted flow of oxygen, capacity to retain water, and simultaneously maintain a low bulk density. This last property of the soil structure means that biochar is a low compact material, allowing space in the soil for the growth of healthy strong roots. The porous nature of the char even has a tendency to suck nutrients and water into itself from surrounding earths and hold them. Since the soil bulk density is low, the capacity for holding water remains very high and very conductive as the biochar attracts water during wet periods and retains it awaiting the dry seasons when it will be available for plants. The increased porous structure of biochar compared with other soils structures has miraculous benefits for plants. In addition to this, it serves as breeding grounds for microorganisms, sustaining their development and activity nurturing healthy plant development. Additionally, biochar is carbon negative. Unlike many different plants and soils, which are neutral, biochar has the proven ability to sequester carbon from the atmosphere. This is due to the process by which the biochar is created.

3.2 Biochar as a tool for carbon sequestration

As a material biochar has inert properties, meaning that it is not biologically or chemically reactive. About 50% of the carbon retained from biomasses, plants, and manure is stored in biochar after undergoing the pyrolysis process. Since biochar is so biologically and chemically unreactive it is greatly resistant to weathering or decomposition of any kind. Thus, biochars, or *terra preta*, created over 2000 years ago in the Amazon Basin still hold their value as a desirable, fertile soil. Soils around the world also contain biochar deposits that are a result of naturally occurring events such as grassland and forest fires. In fact, areas high in naturally occurring biochar, such as the North American Prairie (west of the Mississippi River and east of the Rocky Mountains), are some of the most fertile soils in the world (Krull et al., 2008, Skjemstad et al., 2002).

Biochar can be a simple yet powerful tool to combat climate change. As organic materials decay, greenhouse gases, such as carbon dioxide and methane, are released into the atmosphere. By charring the organic material, much of the carbon becomes "fixed" into a more stable form, and when the resulting biochar is applied to soils, the carbon is effectively sequestered (Liang et al., 2008). It is estimated that use of this method to "tie up" carbon has the potential to reduce current global carbon emissions by as much as 10 % (Woolf et al., 2010). Biochar is produced from feedstock, or organic material, that is heating in a limited or no oxygen environment.

3.2.1 Pyrolysis

Pyrolysis is the thermochemical decomposition of various organic materials into carbon rich solids, bio-oils and a non-condensable gas products by heating the materials at relatively low temperatures (less than 700°C) in low oxygen or no oxygen chambers (Bridgwater and Peacocke, 2002; Demirbas and Arin, 2002; Brownsort, 2009). This process of decomposition converts the biomass into three products:

1. A non-condensable gas product also known as 'syngas' or 'pyrolysis gas' containing carbon monoxide (CO), carbon dioxide (CO_2), hydrogen (H_2), methane (CH_4) and higher hydrocarbons;
2. A bio-oil, which is a liquid product also known as pyrolysis oil or bio-crude;
3. A solid charcoal or char with high carbon content, which has various uses; this is called biochar, or coke (Brownsort, 2009).

Essentially, syngas and bio-oil are the main products of thermochemical decomposition and biochar is just a by-product. The cost and scale of biochar production for soil amendments in agriculture are commercially viable through the processes of fast and slow pyrolysis.

Slow pyrolysis of biochar is a product of traditional heating of feedstocks under oxygen-limiting conditions, which helps for cooking and house-warming purposes. It is obtained by heating the feedstocks at temperatures from 300°C to 800°C at atmospheric pressure for hours to days (Brewer and Brown, 2012). The fast pyrolysis aims at maximizing the production of bio-oil by rapid quenching of vapor produced from burning biomass at higher temperatures (400°C–1000°C) with fast heating rates, typically higher than 300°C for a few hours (Brewer and Brown, 2012; Mohanty et al., 2013).

The production of biochar typically releases more energy than it absorbs, though this is dependent on the moisture content of the feedstock used (Lehmann, 2007). The great amount of heat and gases released during this process can be trapped and used to produce electricity for example. One sustainable solution for feedstock is waste biomass or green waste from municipal landscaping, agriculture and forestry (Hunt and DuPonte, 2010). This model of biochar production provides a cyclic solution where energy can be saved, reformed, and reused. The nature of carbon sequestration and exchange of this product make it able to serve as a great soil amendment.

The stability of biochar in soils is a significant issue and one of particular interest to soil physicists because the study of this material may help understand how long after its application the biochar can remain in the sol and contribute to the mitigation of climate change, as well as continue to provide benefits to soil, plants and water qualities. The conversion of carbon in biomass to biochar carbon through pyrolysis can sequester 50% of C that would otherwise be released into the atmosphere. Compare that with the 3% that is sequestered through a simple burning process. Many studies have shown that the typical Mean Residence Time (MRT) of biochar in soils falls into centennial and millennial figures (Lehmann et al., 2006).

This carbon retained from the slow, cooler burning of agricultural wastes produces a charcoal and acts as a carrying agent for water and nutrients, making it unusually capable of attracting and retaining vital nutrients like phosphorus, calcium, and nitrogen (Churchman and Landa, 2014). The slow, cooler burning process that is actively managed is named the slash and char method by archeologists. This differs from the typical method known as slash and burn which is simply burning material at a high temperature until it turns to ash. As archeologists wondered how the Amazonian civilizations sustained themselves and multiplied in their tropic region these two types of black carbon char provided a solution (Churchman and Landa, 2014). The carbon produced through the slash and char method was able to remain stable in the soils for hundreds of years. This is key for the problems facing the Amazon today as forests are being depleted to make way for unsustainable agricultural practices. The poor quality of tropical soils without the use of biochar means they only sustain crops for a few seasons before farmers have to move on to cutting down more forests for new crops.

Luckily, new information about biochar and its role in improving modern agriculture and sustainably soil is readily available, and almost everything that we know about biochar is based on university research programs as well as private research institutes. Lehmann (2007) in his works states that trapping carbon in biomass through low temperature pyrolysis can be sustained for hundreds and even thousands of years. Additionally, biomass that gas undergone pyrolysis does not need to be maintained as new forests and plants, is not vulnerable to forest fire or decomposition, and does not cease to be active as a carbon absorbing force due to the fact it is teeming with microorganisms.

3.2.2 Polycyclic Aromatic Hydrocarbons (PAH)

The capability of biochar to improve cation exchange capacity, nutrient transport, and water retention properties in soils, as well as maintaining stability over time, makes it an excellent sequester of carbon. However, biochar contains various concentrations of a known carcinogen called polycyclic aromatic hydrocarbons (PAH). The content of this carcinogen can potentially reduce the positive effects of biochar on soils. Luckily, PAH sorbs strongly to black carbon and since biochar is a form of black carbon this makes PAH immobile and unavailable for plant sorption. The quality of biochar therefore greatly depends on the concentration of PAH, which is mainly affected by production conditions.

(Scott et al., 2014) ran an experiment to understand how PAH acts in biochar produced by pyrolysis at different temperatures (450°, 550°, and 750°C). They produced a PAH compound which was amended to biochar products to see how well it was able to bind with the black carbon and how much of the produced PAH was still bioavailable after the process. The biochar at each temperature was subdued to a process of artificial aging, where it could simulate different field conditions. The processes of aging were (1) freezing and thawing on a daily schedule, (2) incubaton at 60°C, and (3) incubation at 110°C. All samples were weighed daily and deiononized with water to maintain an equivalent 40% of field capacity. Their results showed that about 90% PAH remained on biochar produced at

450°C, 85% PAH on biochar produced at 550°C, but only about 5% or less of the added PAH remain in the biochar produced at 750°C. Biochar produced at higher temperatures assures the quality of the material and makes it less vulnerable to the negative effects of PAH, which if found in greater concentrations, can classify the biochar as a waste material. Figure 1 shows a graph of the remaining content of PAH levels after the aging process of each biochar produced at different temperatures. The biochar produced at 750°C showed the lowest remaining concentrations of PAH throughout each aging process.

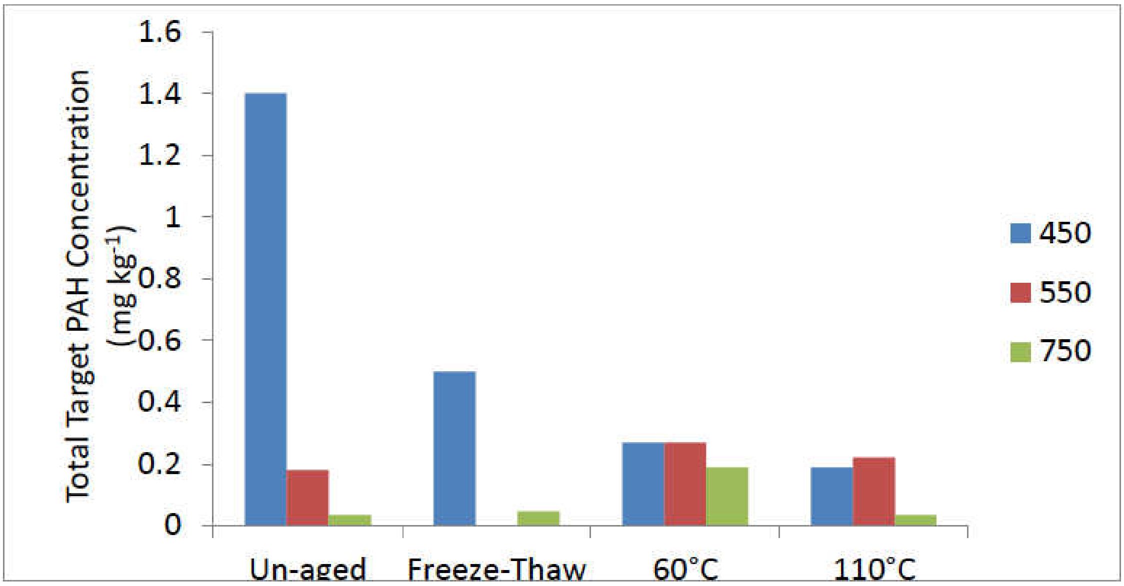

Figure 1*. Remaining content of PAH levels after the aging process of each biochar produced at different temperatures (450, 550 and 750°C) (graph taken from: Scott, J., 2014).*

3.3 Effects of Biochar Amendments to the Soil

3.3.1 Effects of Biochar on Plant Growth

The properties of biochar have several significant and positive effects on the growth cycle of plants as well as beneficial uses in composting. Recent studies in both tropical and temperate climates have proven that biochar increases the rate of plant growth, microbial activity and water retention, while reducing nutrient leaching (Hunt and DuPonte, 2010). One study done by Major et al. (2005) on native Hawaiian soils, Colombian Oxisol, proved that total aboveground plant biomass increased by 189% when biochar was applied at a rate of 23.2 t/ha. Similarly in Brazil, native plant species increased by 63% in places where biochar was introduced. In addition, studies carried out by Rondon et al. (2007) and Warnock et al. (2007) showed that biological nitrogen fixation and myccorhizal relationships in common beans increased with biochar amendments. However, distinct soil conditions and quality of feedstock used to create the biochar can affect the performance of the final product and cause negative effects on plant growth.

Some studies was provided that plant growth has decreased due to nutrient imbalances associated with the temporary pH levels of fresh biochar, as well as volatile or mobile matter (MM), which is made up of tars, resin, and other short-lived substances that remain on the surface of biochar just after production (McClellan et al., 2007). Fresh biochar commonly has a high (alkaline) pH level that shows significantly positive effect on degraded, acid soils. However, if the pH of soil becomes overall too alkaline, the transfer of nutrients to plant suffers. Microbial activity is able to decompose the MM of a fresh product and turn it into nutrients for plants, however, this process requires a lot of energy in the form of nitrogen and soil elements, making nutrients temporarily unavailable for plant uptake (McClellan et al., 2007; McLaughlin et al., 2009).

All of these initial imbalanced are later corrected as MM decays, pH neutralizes, and nutrients are released. In fact, studies have shown that the beneficial effects of biochar on plant growth improve overtime after it has been introduced to the soil (Cheng et al., 2006, 2008; Major et al., 2010). Thus time, proper management and distribution are key factors to consider. The time factor is likewise relevant when biochar is applied as a component of composting, where it can increase microbial activity and reduce nutrient losses. At the same time the pH level of the biochar becomes balanced, mobile matters is decomposed and turned into massive amounts of available nutrients, and microbe activity increases significantly in the process (Dias et al., 2010).

3.3.2 Nutrient Availability in Soils with Biochar Amendment

Nutrient availability for plants is based on how well they move around in soil and their solubility in soil. In a simplified way, the factors that affect nutrient availability include the total porosity of soil, cation exchange capacity, and the presence of soil organic matter capable of digesting minerals or oxidizing them to become soluble in soil and therefore successfully be transported through plant roots. All of these factors generally make up the quality of a specific soil and varies in every region and temperate conditions. Good quality soil supports the transportation of vital nutrients N, P, Ca, Zn, K, and Cu, and is able to retain water for plant growth.

Ferrasols are not tampered soils naturally occurring in tropical and subtropical regions of the world that vary in structure, mineral content, and pore size. Lehman et al. (2003) present, that certain Ferrasols are naturally suitable for plant development due to the features mentioned above. However, many soils of this type due to environmental conditions and structure simply cannot sustain nutrients or plant development. Such are the upland soils in humid tropics such as the Amazon basin. These soils are highly weathered and thin due to heavy rainfall and a low capacity for nutrients available to plants. Tropic soils have a large presence of iron and aluminum oxides, greatly limiting the cation exchange capacity, low soil organic matter contents and low pH levels, meaning that it is acidic. In sub soils of the Amazon basin high amounts of nitrate were reportedly found, which are not soluble. In these conditions even applied nutrients are quickly leached below the roots.

Anthrosols based on biochar content act as a remediate for poor ferrasols. When char is created by the process of slow pyrolysis and tilled with the untouched soils it increases the carbon and soil organic matter content, fixes the soil structure and porosity, and reboots the cation exchange capacity (CEC). The porosity of these anthrosols attract and retain both water and nutrient and due to the high carbon content these nutrients stay put for many years, making the anthrosols valuable for farming.

3.3.3 Cation Exchange Capacity in Biochar Treated Soils

Nutrients in soil soluble form mean that they are in a ready state to be taken up by plants through the roots, a majority of basic nutrients are taken up by plants as cations, or positively charged ions. Most minerals have either positively or negatively charged ions. CEC is the ability of cations held on clay and organic matter particles to be replaced by another anion, making them exchangeable. The total amount of negative charge, or anions that a specific soil sample can hold is defined as it cation exchange capacity (Mengel, 1914).

Since the CEC of soil is based on the presence of clay and organic matter, it can be measured based on the texture and color of the soil.

Biochar additions to soils positively affect pH values and CEC, and play a major role in biogeochemical processes such as adsorption reactions (Schmidt and Noak 2000). Anthrosols with high biochar content were found to possess high mineral cation availability (Lima et al., 2002), and a neutral pH value, compared with surrounding forest soils which were highly acidic and leached of almost all its nutrient content (Lehmann, 2006). The low CEC of naturally occurring Ferrasols in the Amazon basin are attributed to low soil organic matter content and the presence of kaolinite, a highly weathered clay material (Sombroek, 1966). Such conditions prevent the ability for soil to retain mineral cations in their soluble form and prevent the oxidation of minerals from the non-soluble forms. Glaser et al. (2003) suggest that the main reason for increased CEC in Amazon anthrosols is due to the oxidation of aromatic C and the formation of carboxyl groups, which are functional chemical compounds with a net negative charge in the pH of soils. Furthermore, the formation of carboxyl is the result of surface oxidation of biochar, or the adsorption of highly oxidized organic matter onto anthrosol surfaces (Lehmann et al., 2005).

3.3.4 Soil Water Retention in Biochar Treated Soils

The soil water retention, along with saturated hydraulic conductivity, are two of the key most important hydraulic properties that directly influence soil and water management problems related to ecology, agriculture, and environmental issues. The soil water retention curve (SWRC) is used to express the amount of water (water content of the soil, θ) that has been retained under equilibrium at any given matric potential (h). Soil water retention is an important hydraulic property related to overall porosity and is strongly affected by soil texture and structure, and by organic matter content (Tuller and Or, 2003).

Two main types of forces determine the water content of a soil; these are; (1) positive forces, such as adhesion and cohesion, which enhance the soil's ability for retaining moisture, and (2) negative forces, such as gravity, evaporation, and growing plant root uptake, which all pull the water out of the soil (Lal and Shukla, 2004). Water flow and distribution within the soil matrix is modeled by the soil water retention curve (SWRC), by graphing the volumetric water content depending on the matric potential, $\theta(h)$. It provides a good understanding of the before mentioned properties about soil in addition to nutrient solubility and contaminant transport through the environment, and also when the water is available to plants within a particular soil type. The matric potential is a property attributed to the capillary and adsorptive forces acting between liquid, solid, and gaseous phases (Tuller and Or, 2003). The capillarity, or structure of pores and shape change from one type of soil to the next. The bulk density of a soil has a lot to do with the potential.

Figure 2 below demonstrates the typical SWRC for three different soil types:

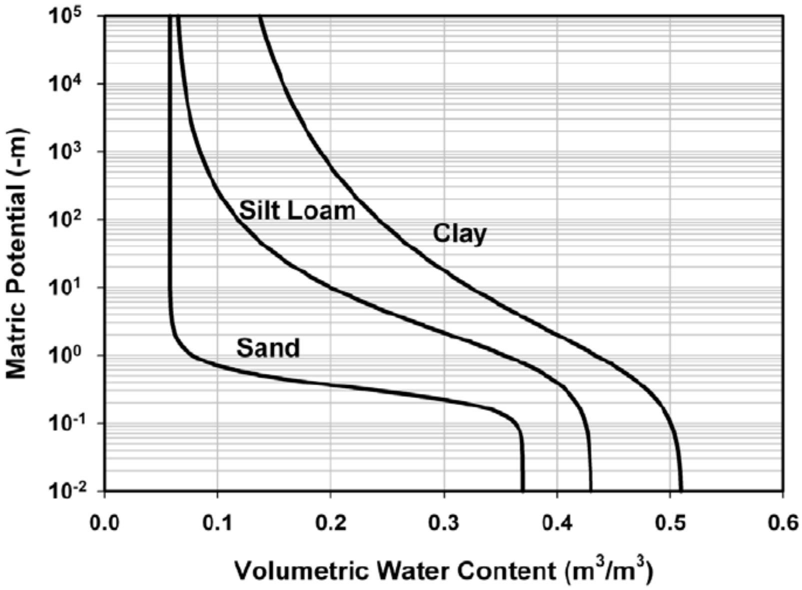

Figure 2. *Typical SWRCs of sand, silt loam, and clay soils (Tuller and Or, 2003).*

The effect of biochar on soil pores is stability, by increasing and maintaining uniform pore shapes and sizes it both decreases the bulk density of the soil matrix and increases the water retention rate, which inevitably is related to hydraulic conductivity. Because of its tendency to create better microbial activities this water retention turns into long-term water holding capacity.

Biochar increases the water holding capacity of soil. The carbon-rich content of both biochar and charcoal have shown to increase soil water retention (Lehmann et al., 2006; Laird et al., 2010; Spokas et al., 2010; Karhu et al., 2011), as well as hydraulic conductivity within degraded soils. A study by Asai et al. (2009) conducted in Laos found that higher biochar application rates improved soil water permeability and holding capacity, which improved overall plant water availability. Blackwell et al. (2009) found that applying biochar to crop fields at a relatively modest rate of about 1 t/ha increased crop yields simply due to better crop water supply. Thus biochar is one of the ways of saving money and water resources on expensive irrigation systems that are commonly utilized today for depleted soils. In addition, well-manufactured biochar material does not pollute or degrade water sources.

3.3.5 Saturated Hydraulic Conductivity in Biochar treated Soils

The movement of water through soil pores is a result of the difference in potential energy within a porous soil matrix and is always described in terms of this potential difference. The difference in total water potential (the sum of gravitational, pressure, and osmotic potentials) is what forces water to move from an area of high energy (potential) to low energy. During the flow of water through saturated soil the water content remains constant, therefore, only positive potentials drive the transport of water through the matrix (Lal and Shukla, 2004).

Saturated hydraulic conductivity (K_s) describes the ease of fluid movement through saturated porous media and it can be directly measured with flow-through experiments or estimated using theoretical or empirical models. Theoretical models require significant knowledge of porosity, tortuosity, pore shape, grain density, and specific surface area of solid grains. Explaining how biochar effects the movement of water through soils has been a particular focus of research that suggests biochar not only stimulates the movement of water through its own pores but also through the gaps between the biochar and the grains of soil, or interstellar spaces.

Ouyang et al. (2013) performed an experiment that tested the effects of biochar admixture on soil hydraulic properties as well as aggregate structure. The objective was to see how biochar worked with different structures of soil. For their experiment they extracted two soil types; silty-clay loam (SCL) and a sandy loam (SL), both of which were homogenized and mixed with 2% biochar sieved on a 2 mm sieve. The soils with and without biochar were tested regularly every 10 days for 90 day total. During each sample period, an incubation experiment was run to determine the soil aggregation on each sample type, four times, and the K_s and water retention of each sample was measured three times.

Their results showed that the biochar amendment did promote the formation of macro-aggregate structures in both soils, although the increase was more significant in the silty-clay loams than the sandy-loam. The biochar admixture demonstrated an increase in the K_s of both soils and decrease in residual water contents, as well as changed the function of the water retention curve significantly. The authors attribute this to the soil structure changes. They believe an improvement in soil structure would have an even greater impact on the K_s of the soils, and testing higher concentrations of biochar would have been beneficial for the experiment. Nonetheless, biochar increased the macro-aggregates of the sandy and silty-clay loams while simultaneously decreasing the bulk densities of both producing immediate stimulation of unsaturated water flow. According to Hillel (1982), the soil water retention function is mainly dependent on the soil structure, such as larger pore sizes and soil aggregates.

Barnes et al. (2014) tested the effect of adding biochar to different materials. Early on they discovered that in sand, through which water typically drains very quickly, biochar slowed the movement of water by an average of 92%. In clay-rich soils that usually retain water, biochar sped up movement by more than 300%. That is significant, Barnes says, because even though clays can hold large amounts of water, moisture does not move well through the grains and reaching plant roots. These results effectively prove that biochar added to soils of different texture acts to stimulate the movement of water from places of high activity to places of low activity.

In 2014, Barnes and Gallagher conducted an experiment testing the influence of biochar amendments on the water movement and nutrient flux of different soils. To test this response of K_s and dissolved nutrient fluxes to biochar amendment, they conducted the falling head experiments across six materials; sand, sand+biochar, organic soil, organic soil+biochar, clay, and clay+biochar. A sample of 150 g was collected for each material, which was distributed evenly between three identical columns; 50 g per column, with polyester mesh screen at the bottom. To achieve a uniform bulk density in each sample the materials were packed into the columns in four equal increments with a consistent applied force. The initial soil lengths in the column were then recorded. The bulk density was determined for the soil materials as well as the soil material+biochar mixture using the dry mass ad column dimensions (height of soil materials, diameter of column) at the start of the experiment. Additionally, particle size distributions of soil+biochar mixtures were estimated using the proportional masses of each material and appropriate particle size data. Biochar was maintained at 10% of the total mass in the columns that contained biochar. This amendment rate (10% biochar: 90% soil) is considered high and more than what is likely to be applied to agricultural fields, however, it provided enough altercation of the soil-water to system to observe significant effects across three contrasting soil materials.

Similar to previous experiments, the addition of biochar decreased the K_s of sands by 92% and 67% in organic soils, but increased K_s by 328% in clay-rich soil. The goal of their research was also to observe the nutrient flux of C and N within the soils. Changes in the magnitude and direction of these nutrients varied depending on soil type, particle size and composition. With the biochar increasing C flux organic-poor sand, decreasing it from organic-rich soils, and retaining small amounts of soil derived N.

3.3.6 Soil organic matter

Soil organic matter (SOM) is the presence of microbial activity that likewise contributes to water retention, soil stability and aggregation of a soil (Glaser et al., 2002). SOM changes the physical properties of the soil matrix, giving it a more porous structure allowing soils to retain more moisture. In fact, the dark colors of biochar treated soils are a result of high organic carbon content, which is three times greater than in any non-anthrosols in the Amazon Basin (Churchman and Landa, 2014). SOM is widely known to possess stable characteristics as a unique chemical compound resembling humus substances; however, it is debated on whether a humus substance is the proper way to describe it. According to Lehmann and Kleber (2015), SOM is not a stable substance but rather a constant cycle of decomposing matter. The cycling of nutrients in soil is the result of this decomposition.

Organic matter is a source of nutrients for plants that are both readily available and stored away for future use by the plants. Soil organisms draw energy from organic matter, which help the formation of micro- and macro-aggregates and consequently promote the infiltration of water and air into stable soil structures (Tisdall, 1996). The emphasis of soil structure is determined by the influence of SOM on soil water retention and the cycle of pesticide within the soil. The ease of soil compaction is also determined by the SOM content (Gregorich et al., 1994, 1997; Kay, 1998). Furthermore there is a direct relationship between SOM and soil aggregation. Therefore SOM plays an important role in soil stability against erosion, leaching of nutrients, and overall benefits to air and water infiltration qualities (Feller and Beare, 1997).

An Australian study conducted by Robertson and Thornburn (2001) examined the effects of crop residue on the soil C and N cycling under sugar cane wastes which is usually burned. Since organic matter content of these types of wastes is lost when burned there has been a recent change is these practices replaced by the so-called trash blanket (TB) system, where the crop residue is spread over the field and left to decompose its organic matter. The experiment compared the cycling of nutrients and biomass development of lands treated with burnt trash and those treated with unburnt trash (agricultural waste). They tested these on lands with different climates and agricultural ages.

Their experiment was conducted over the course of six years in which the TB was cultivated into the soil up to a 155 cm depth, allowed to decompose and new TB was reapplied next season, the same was done with the burnt trash. Samples were extracted regularly from different depths and tested for C and N activity. Their results showed that greater soil organic C, total N, and microbial biomass were found under fields treated with unburnt TB, than in earlier experiments when the burnt waster was applied. This proves that burning is an unsustainable process for agricultural waste management since much of the nutrients are lost in burning and taking the extra effort to till unburnt wastes into the land has long-term benefits. This trend is similar to the way biochar develops soil organic matter overtime but at slower rate.

3.3.7 Miccorhiza

Microbial populations are diverse and intensely competitive, they are able to thrive in environments of varying light, oxygen, and nutrient supply, as well as environments of extreme temperature, acidity, alkalinity, and salinity conditions (Tortore and Funke, 2016). This is mainly due to the fact that microbes and specifically fungi envelop large taxa. For soil applications, symbiotic relationships between plants and microbes are vital. A symbiotic relationship is any close association between two unlike organisms, such as plant roots and fungi that is beneficial to one or both of them. Mycorrhizal fungi fit this category since they extend the surface area through which plant roots can absorb nutrients, phosphorus in particular, while depending on the plant roots for proper development (Tortore and Funke, 2016).

Nutrient availability and solubility for plants relies on rock digesting microorganisms that can oxidize specific nutrients and synthesize the nutrient so that it is soluble within soil and ready for root uptake by plants. Fungi are generally categorized into two big groups known as Saprobes, which thrive in soil, water, and decaying plants and animals, and Parasitic or mutualistic symbionts that feed on living organisms. Myccorhizal fungi are difficult to fit into any one of these groups as they make up a heterogeneous group of fungi taxa that form in and around plant roots, increasing mineral nutrition, influencing water adsorption and growth, and protecting the host plant from diseases. In exchange, plants provide breeding grounds for myccorhizal fungi.

The word 'myccorhizal' is derived from the Greek words for 'root' and 'fungi,' and the relationship between plants and myccorhizal fungi is very dependent. Myccorhizal fungi can spend only a part of their life cycle as free living organisms but mostly develop alongside plants, just as well over 90% of plants species including forest trees, wild grasses, and crops are reliant on the fungi for proper development. From a broad spectrum, Myccorhizas are divided into two larger sub groups known as endomyccorhizals or ectomyccrohiza (EM), depending on whether the fungi develops colonies inside the root cells or within the spaces between cells respectively. Furthermore, the endomyccorhizas, which form intercellular colonies, are divided into even smaller categories; the orchid, ericoid, and arbuscular myccorhiza (AM)(Bonfante and Genres, 2010). The fact that myccorhiza makes up such a broad genome and facilitates several strategies for building colonies makes it even more useful for forming symbiotic relationships with plant roots (Bonfante and Genre, 2010).

Myccorhiza depend on carbon to complete their life cycle. In fact the relationship of AM with 65% of plant species is based on the fungi supplying vital nutrients nitrogen and phosphorus in exchange for carbon from the host plants. In fact, host plants transfer up to

20% of their photosynthetically derived carbon to AM. Furthermore, in this type of symbiotic relationship, neither the host plant nor the fungi are in control of the relationship. Both are able to adjust their tributes based on their own needs for nutrients. Although many plants are able to directly uptake soluble nitrogen and phosphorous from the soil, AM fungi provide another pathway for this to happen through their own symbiosis. Neither of these pathways is more or less efficient, however, it has been found that carbon that is transported from the host plant in the form of sucrose to the AM fungi is synthesized and in so doing, stimulates the transport of N and P to the plant (Felbaum and Mensah, 2012). The various nutrient transport and exchange between the AM fungi and host plants demonstrates the importance of a symbiotic relationship that can adapt to a means of thriving independently however, the basis of which is driven by carbon supply.

3.4 Measurements of Saturated Hydraulic Conductivity

3.4.1 Laboratory Measurements of Saturated Hydraulic Conductivity

Two standard methods of measuring K_S in laboratory are by falling-head permeameter and constant-head permeameter. In the falling-head experiment, the water head, or internal energy of a fluid due to pressure exerted onto it, decreases with time. This initially high water head is suitable for calculating low hydraulic conductivities. The constant-head method is a good tool for measuring the hydraulic conductivity of a specific layer vertically or horizontally. The principle behind this method is that a constant difference in head is created over an undisturbed soil sample in a Kopecky steel ring. At certain times, the volume of water that has flowed through the sample is measured. From this discharge, the size of the soil sample, and from the difference of head, the value for hydraulic conductivity can be calculated (Hillel, 1998; Stibigner, 2014).

The methods for measuring the hydraulic conductivity of saturated soils in laboratory were reviewed by Klute and Dirksen (1986). Measurements should be carried out preferably with undisturbed core samples taken directly from the field, however, can be made either with dried or fragmented samples but must be packed into flow cells in a standard manner (McIntyre, 1974). The two types of laboratory permeameters: constant head and falling head, are both based on Darcy's Law (1856), the difference being the maintenance of pressure in the first one and the decreasing pressure in the second. It is important to note that Darcy's law only applies to stationary, laminar flow, in other words, where there is non-turbulent movement of adjacent layers of fluid relative to another (Hillel, 1998). Laminar flow prevails in silts and finer materials for the most commonly occurring hydraulic gradients found in nature (Klute and Dirksen, 1986). With coarse sands and gravels in excess, non-laminar flow conditions may be created and Darcy's law would not be applicable, hence the measurement of K_s using permeameters would be impossible.

3.4.2 Constant Head Permeameter

The constant head permeameter is used to measure K_s for non-cohesive sediments such as sands. Darcy's law is applied to a soil sample of length L and a cross sectional area A through which a constant flow rate q is generated by a constant head differential, ΔH. Figure 3 shows the schema of a constant head experiment.

Saturated hydraulic conductivity in m/s is calculated from the volumetric water flux V (m^3) divided by the soil sample area A (m^2) and time t (s), the length of the soil sample L (m) and the hydraulic head gradient ΔH (m) along the flow direction. According to Darcy (1856), the flux density q (m/s) in laminar flow is proportional to the hydraulic gradient (eq. 1):

$$q = \frac{V}{A \cdot t} = -K_s \frac{\Delta H}{L} \quad \text{and} \quad K_s = \frac{LV}{\Delta H A t} \qquad \text{(eq. 1)}$$

3.4.3 Falling Head Permeameter

The falling head permeameter is used for cohesive sediments with low hydraulic conductivity. The time t during which the head in a tube of radius r, attached to the permeameter and supplying the sample, falls from H_0 to H_1 is measured with such a permeameter. Figure 4 shows the falling head apparatus.

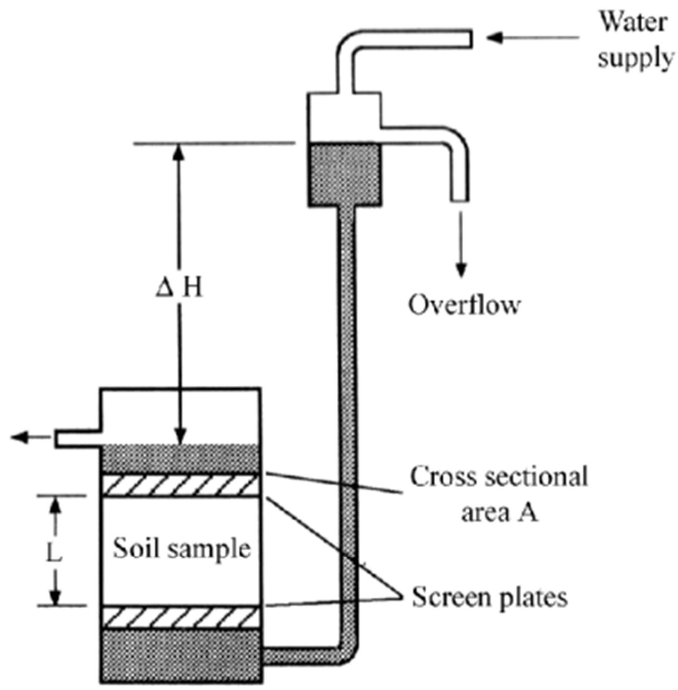

Figure 3. *The Constant head permeameter (source: http://echo2.epfl.ch/).*

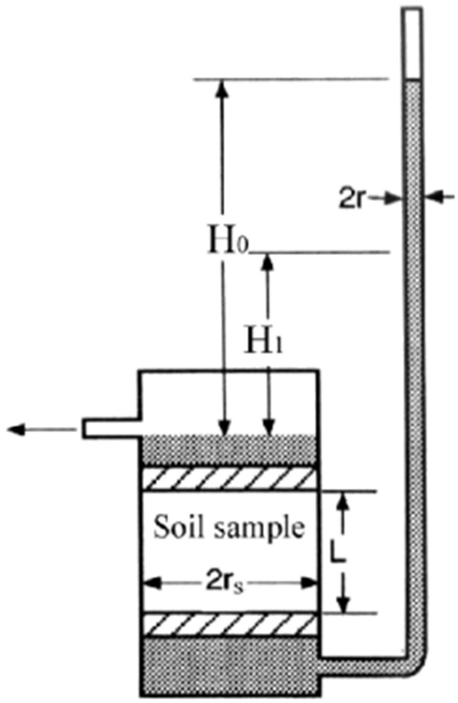

Figure 4. *The falling head apparatus (source: http://echo2.epfl.ch/)*

By solving for the different cross sectional area of the sample πr_s^2 and the cross sectional area of the tube πr^2, as well as the time t that the water falls from H_0 to H_1, the following basic equation was derived for the proper calculation of K_s (eq. 2):

$$K_s = \frac{r^2 L}{r_s^2 t} \ln \frac{H_0}{H_1} \qquad \text{(eq. 2)}$$

Where r (m) is the radius of the tube, r_s (m) is radius of the cylindrical sample, L (m) is the height of the sample, t (s) is time, H_0 (m) is the initial water level in the tube, H_1 (m) is the final water level at the time t.

The laboratory measurements and equations for calculating K_s have been repeated numerous times and internationally accepted as the standard for conducting laboratory procedures on a variety of soil types and structures. Experiments related to biochar admixtures also coincide with these methods.

3.4.4 Field Measurement of Saturated Hydraulic Conductivity

There are numerous methods for measuring near-surface saturated hydraulic conductivity of soils and indeed this property of soil is the most important to evaluate. The most common methods for assessing the K_s of undisturbed soil in situ include: the Auger hole method (Hooghoudt, 1936; Ernst, 1950), if the groundwater level is available in measured layer; the Double ring infiltrometer (Parr and Bertrand, 1960; Matula and Dirksen, 1989), the Guelph permeameter (Reynolds et al., 1985), the Pressure infiltrometer (Matula and Kozáková, 1997). All of these methods are performed in situ at or near the soil surface. There is no single method that is ideal for determining K_s in situ as each method has its limitations and is chosen based on project requirements, time availability, soil type, and budget. There is however a need for a reliable, practical saturated hydraulic conductivity field method for the vadose zone that requires little specialized or expensive equipment. Such a method could benefit both consultants who operate on tight budgets and hydrogeologists who are working in remote areas or countries with limited infrastructure (Lewis, 2016).

To invent a means of meeting this low cost need for K_s measurement or field estimation (Lewis, 2016) created a method using simple, affordable tools which can be found in any hardware store and are very convenient for application on undisturbed and artificially packed samples in the field (although it is measured on taken samples and thus it is not considered as in situ measurement). His falling-head experiment requires a thin-walled, rigid metal tube with an internal diameter between 0.05 – 0.2 m and length between 0.5 and 2 m. This is used to carefully hammer into the soil at a vertical drive between 10-15 cm deep. This is then extracted carefully from the surface with a shovel so as to not loose the sample from the bottom of the tube before securing it with filter paper and metal mesh duct taped onto the bottom of the tube. The method proved successful when using drainage downspouts and narrow gauge ventilation ducts as thin-walled metal tubes, coffee filters for filter paper, and window screening for the metal mesh.

The next step in Lewis' experiment is to place the sample tube into a wider container and begin filling it to the brim with water every 15 to 20 minutes. Once the water level has reached over the soil sample in the tube it is assumed that the sample has reached saturation. Once saturation has been reach water is carefully poured into the top of the sample tube, which initiates downward flow through the soil. This flow is left to stabilize for 30 minutes. The rate of decrease of water head inside the tube is easily measured by hand.

The method has been successfully applied to surface soils up to 3 m in depth, repacked samples obtained by drill cutting up to 10 m deep, and undisturbed soil cores up to 5 m deep obtained with a direct push drill rig. It is important to note that samples obtained from grinding drill methods increase the proportion of fines in the sample and bias the falling-head analysis. Likewise, methods that require drilling mud cannot be used to obtain samples for this type of analysis.

Figure 5 shows the scheme of Lewis' experiment and the changing water head.

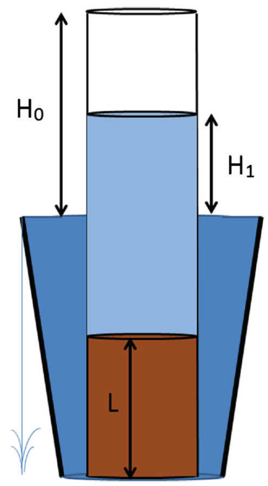

***Figure 5**: The water container filled to the brim (dark blue) allows a constant lower head boundary. H_0 is the initial head at the start of the test and H_1 the head after a period of time. L is the length of the soil core inside the tube.*

3.5 Homogenized soil core samples

Measurement of saturated hydraulic conductivity in situ is generally better and more reliable than lab measurement employing the core rings of small volumes. Soil structure has a key influence on a measured value of K_S, thus the undisturbed soil should be used. However, For artificially repacked samples (Lewis, 2016) recommends repacking the soil directly into the tube with the bottom filter paper and mesh already installed. The samples have to be packed to the natural bulk density of the particular soil. To maintain uniform bulk density the Proctor method of compaction (discussed in the next section) is recommended using three lifts of soil, modifying the number of blows to reproduce the natural bulk density (Das 2010).

In some specific cases the artificially repacked soil core samples are being used, e.g. to eliminate the influence of natural soil variability. Recently, Mohawesh et al. (2017) conducted an experiment that tested the effects of soil homogeneity on the hydraulic properties of soil and the transport of water through these soils. To do this they collected samples of five different soil structures at different horizons: (1) Angular-blocky, taken from 40-50 cm depth, (2) Crumble, from the surface soil layer, (3) Angular-blocky from 70-90 cm depth, (4) Granular taken from 5-25 cm depth, and (5) Subangular-blocky from 40-

50 cm depth. A total of sixteen undisturbed samples were collected from each soil horizon in metallic cylinders of 250 cm^3 for testing soil hydraulic properties. In addition to this, an amount of disturbed soil was collected from each horizon in order to be homogenized in the laboratory and tested similarly for hydraulic properties.

To homogenize the disturbed samples, each soil was sieved at 2 mm, then wetted up to about 25-30% water content using regular tap water and a gentle sprayer, mixing the soils as they are being wetted. The team stored the prepared samples in sealed plastic bags to maintain the moisture content and stored them in a refrigerator to prevent the formation of microbial activity which can otherwise affect hydraulic properties. Before testing the samples were packed into 250 cm^3 metallic rings and compressed from both sides using a uniaxial compressor until the desired bulk density is achieved for that soil.

Taking the undisturbed and homogeneous samples of each soil type, each sample was saturated from the bottom with regular tap water then the tensiometer method was utilized to measure the soil water retention and saturated hydraulic conductivity. Their results demonstrated that soil homogenizing decreased the soil water holding capacity (except for the granular soils), as well as decreased the saturated hydraulic conductivity. Another interesting factor that was altered by soil homogenizing the soil was a significant increase in wider soil pores and a decrease in narrow pores (Mohawesh et al., 2017).

For artificially repacked samples (Lewis, 2016) recommends repacking the soil directly into the tube with the bottom filter paper and mesh already installed. The samples have to be packed to the natural bulk density of the particular soil. To maintain uniform bulk density the Proctor method of compaction (discussed in the next section) is recommended using three lifts of soil, modifying the number of blows to reproduce the natural bulk density (Das, 2014).

3.5.1 The Standard Proctor Test

Compacting loose soil fills is the simplest way to increase their stability and load-bearing capacity, usually this is done by using smooth-wheel rollers, sheepsfoot rollers, or vibratory rollers (Das 2010). The Proctor test is conducted in the laboratory to outline specifications for field compaction. This test was first developed and performed by Proctor (1933) and is outlined in the ASTM International as the *standard Proctor test*. To conduct this test three layers of soil are compacted into a 944 cm^3 volume mold, each layer receives 25 blows from a hammer weighing 24.6 N with a 304.8 mm drop. From the known volume of the mold, the weight and moisture content of the soil compacted within the mold; the dry unit weight of compaction can be determined and expressed as (eq. 3):

$$\gamma_d = \frac{\gamma_{moist}}{1+w} \qquad \text{(eq. 3)}$$

Where

γ_{moist} is the moist unit weight of compacted soil (g) and it is calculated as Weight of moist soil in the mold / Volume of the mold

γ_d is the dry unit weight of compacted soil (g)

w is the moisture content of soil (%)

This test can be repeated several times at different moisture contents of the soil (Das, 2010).

3.5.2 Influence of Dry Bulk Density on Soil Hydrophysical Properties

Knowledge of soil hydraulic properties such as conductivity and water retention has many agronomical and ecological applications. The study of the rate of water flow through soil matrices plays an important role in drainage, evaporation, and water uptake by plant roots (Plagge et al., 1990; Kutilek and Nielsen, 1994). Soil volumes are affected by mechanical stresses such as tillage-induced compaction, and internal forces, like wetting and drying phases. The magnitude of these volume changes are affected by the mechanical stability of these soils (Horn et al., 1991; Horn et al., 1995; Ball et al., 1997; McNabb et al., 2001). It is also well known that soils are able to shrink and swell (Peng et al., 2006). However, with respect to the calculation of hydraulic properties, in most cases it is assumed that soils behave like a rigid body.

In order to describe the hydraulic behavior of structured and disturbed soils with different compaction levels, Dec et al. (2008) studied the effects of dry bulk density on the soil water retention curve (SWRC), soil shrinkage, and the collective effect on hydraulic conductivity. They conducted their experiment with arable soils classified as Stagnic Luvisol (IUSS Working Group WRB, 2015) at three different dry bulk densities; 1.2, 1.4, and 1.6 g/cm^3 (they prepared ten replications of each bulk density with 20% gravimetric water content). To ensure uniform bulk densities, the soil was packed into cylinders at carefully controlled densities by means of a "load frame" device. These samples were then saturated by capillary rise for three days.

After statistical analysis of their tests, Dec et al. (2008) concluded that the development of the SWRC is dependent on soil bulk density ad structure, and just as expected, the saturated water content, decreases with increasing bulk density, as demonstrated on Figure 6. The saturated hydraulic conductivity in this experiment was measured with permeameter under instationary conditions. The water flow was measured three times for each sample and the arithmetical mean was determined. The hydraulic conductivity showed to decreased with increasing bulk density due to the smaller volume of coarse pores in the disturbed samples.

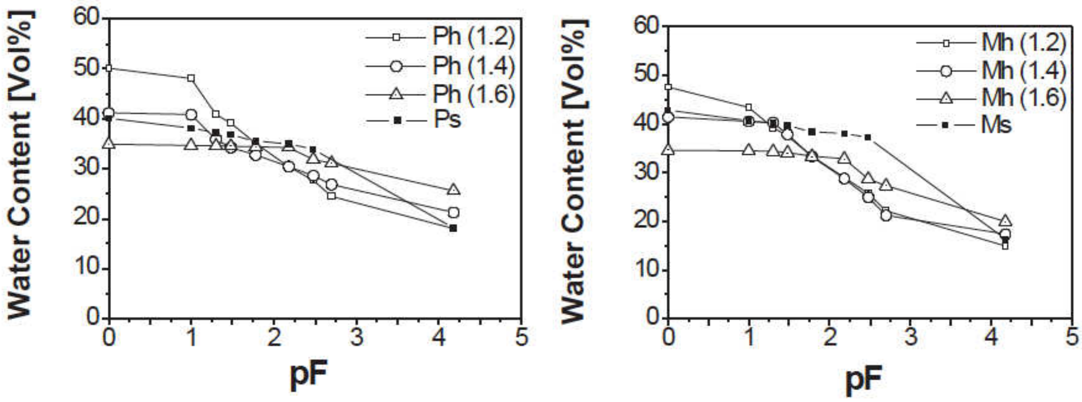

***Figure 6**: The luvisol soil was derived from two tillage treatments; Conventional Plough (P) at 30 cm depth, and Conservation Mulch (M) at 8-10 cm depth. Both instances show the effect of increasing bulk density on the saturated water content (Dec et al., 2008).*

Matula et al. (2016) performed an experiment to test the effective performance of five different soil moisture sensors silica sands and Haplic Chernozem of different bulk densities and salinity levels. The sensors they tested were commercially viable, cheap sensors of the Frequency Domain Reflectometry (FDR) and impedance type, these were; ECH2O EC-10,

ECH_2O EC-20, ECH_2O EC-5, and ECH_2O TE (FDR), and the ThetaProbe ML2x (impedance). For preparing the samples they sieved each soil to 2 mm and packed them into a rectangular calibration chamber with dimensions of 33 cm (length) x 23 cm (width), and 13 cm (height) and total volume of 10 L.

The sand samples were packed at three different bulk densities with the values to be tested by each sensor; (1) loose packing, where the bulk density was between 1.00 g/cm^3 and 1.16 g/cm^3, (2) moderate, bulk density of 1.20 g/cm^3 and 1.35 g/cm^3, and (3) compact packing, dry bulk densities 1.40 g/cm^3 and 1.62 g/cm^3. These bulk densities were prepared for different probes. The Chernozem soil was prepared at one bulk density evaluated at an average of 1.20 g/cm^3, although this was more difficult to maintain at higher soil water contents (29%-39% by volume). When the values for bulk density of the chernozem reached 1.30 g/cm^3 and 1.35 g/cm^3 this level of bulk density was referred to as moderate packing (MP).

When testing the sand/soil samples particular focus was given to the placement of the sensor within the container, the dimensions of the sensor, sampling volumes, and measurement ranges. The performance of each sensor was determined by taking the measured values and comparing them to the accepted values calculated by the gravimetric method, based on water content by volume. In a addition to this, a statistical method of analysis between the accepted and measured values was implemented. The absolute difference (AD) between two real numbers is the distance on the real line between these two points (Doležal et al., 2008).

Figure 7 below is a graph displaying the results of one FDR probe on the various bulk densities of sand based on the factory settings of the probe. Figure 8 is a graph of results of the same model probe on moderately packed Chernozem soil.

It is visible from the two graphs above that the measurements of the probes were less accurate for light structured, loosely packed sand. The moderately pack and compacted sand yielded results closer to the gravimetric value line on the graph, similarly, the measurements on chernozem soil did not stray to far from the mean line. The results of this experiment proved that different probes were applicable to different soil conditions. Since the soil and sand samples were homogenized the conditions affecting the probe performance is namely the bulk density of the particular sample.

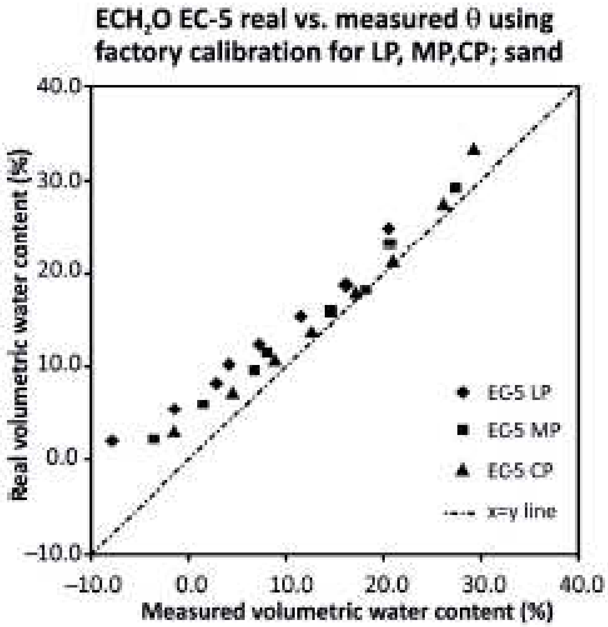

Figure 7. *The ECH$_2$O EC-5 measured values of volumetric water content for silica sand at three different bulk density levels in comparison with gravimetric water content, based on factory settings of the probe (Matula et al., 2016).*

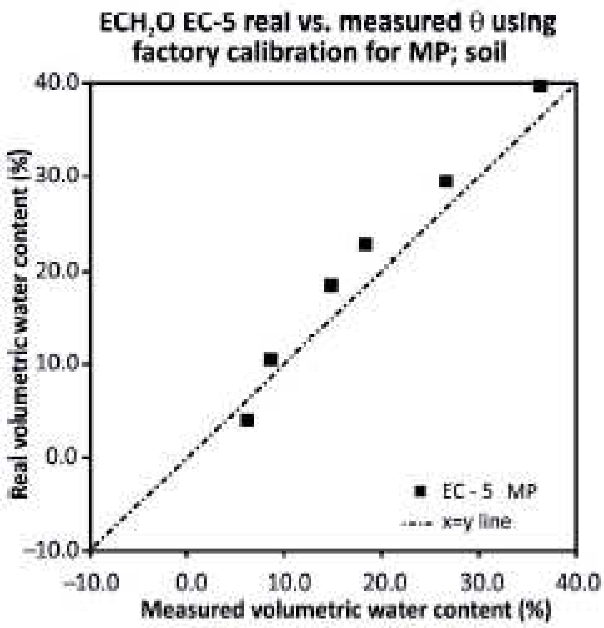

Figure 8*. The ECH$_2$O EC-5 measured values of volumetric water content in comparison with gravimetric water content, based on factory settings of the probe (Matula et al., 2016).*

4 Materials & Methods

4.1 Information about soils

The effect of biochar admixture was tested on four different soil types; Silica sand, cambisol, luvisol, and chernozem. Silica sand was chosen as a neutral model material, since according to Soil Taxonomy soil is defined as the natural medium for the growth of plants, whether or not it has discernible soil horizons (Soil Survey Staff, 1999). Other soils were chosen due to their wide spreading and representation of soils in the Czech Republic. The sampling sites are shown on Figure 9. Each soil has been taken from various fields and has a different texture and structure and hydraulic properties. Thus the addition of biochar is supposed to affect the movement of water differently as well.

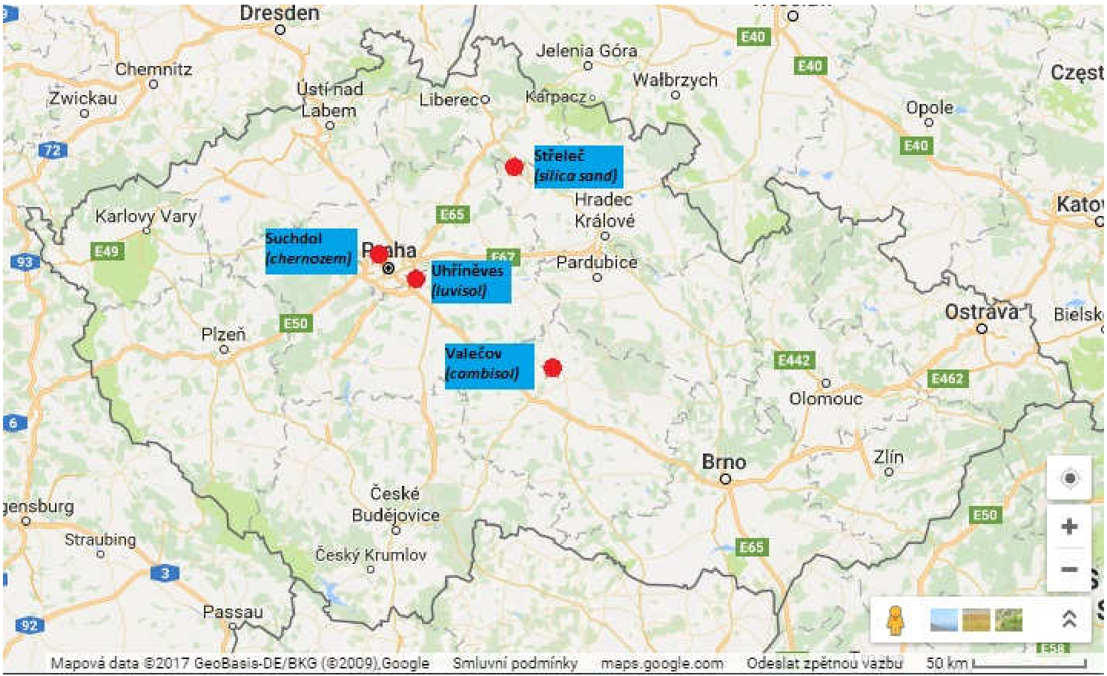

Figure 9. *Locations of the sampling sites (adjusted from maps.google.com).*

The soils were transported to the laboratory and crumbled gently by hand without root material, then sieved on 8 mm sieve (chernozem and luvisol) or 5 mm sieve (cambisol) and stored with the natural water content, however exposed to slow evaporation in room temperature. As much as possible, natural soil aggregates were maintained.

4.1.1 Silica Sand

The silica sand used for this experiment is sorted sand with a commercial name ST56 produced in East Bohemia by a company called Sklopísek Střeleč, a.s., Czech Republic. The sand contains 99% silicon dioxide and its texture is classified as fine and very fine sand. More details about its particle size distribution are given in Appendix 1. It has an average pH 8.0, and it is inert, so it is suitable as a model material for the purpose of this study.

4.1.2 Luvisol

The luvisol samples were taken from the topsoil at the Experimental Station of Department of Plant Production, Faculty of Agrobiology, Food and Natural Resources, Czech University of Life Sciences Prague located in Prague - Uhříněves. The texture class of this soil is a clay loam with an organic matter content of 1,74-2,12% and pH neutral and with good reserve of all essential nutrients. The soil was formed on loess in semihumid climate with the elevation 295 m a.s.l., annual precipitation 575 mm and average annual temperature 8.4°C (Krejčířová et al., 2007; Dvořák et al., 2015). The soil has been under intensive agricultural cultivation and was taken from the field in late summer after preparation for seeding.

4.1.3 Chernozem

This loamy carbonate soil on aeolic loessial substrate was classified as haplic chernozem (IUSS Working Group WRB, 2015) and it was collected from the topsoil at Experimental Terrain Station of Soil Moisture Dynamics of the Department of Water Resources in Prague - Suchdol, Czech Republic, with the elevation approximately 279 m a.s.l., average annual air temperature around 9°C, and average annual precipitation of around 500 mm. Its texture varies around 22-28% clay, 39.5-54% silt, and 22-32.5% sand. The structure is polyhedric and has the capacity to swell and shrink (Doležal et al., 2012; Matula et al., 2014). The soil has been under intensive agricultural cultivation and was taken from the field in late summer after harvest.

4.1.4 Cambisol

The soil formed on paragneiss classified as dystric cambisol (IUSS Working Group WRB, 2015) was collected from the topsoil layer at experimental field of the Potato Research Institute Havlíčkův Brod, Ltd., research station in Valečov in Bohemo-Moravian Highland. The locality has elevation 445 m a.s.l., average annual air temperature 7.2°C, and average annual precipitation 660 mm (Kidane, 2016). The field has been under intensive agricultural cultivation and the soil was taken in early spring before cultivation.

4.2 Biochar Properties

The biochar used for this laboratory experiment was obtained from a manufacturer BIOUHEL.CZ, s.r.o. It was produced from a mixture of silage maize resting in a biogas station and wheat straw, at a ratio of about 1:1. The biochar underwent pyrolysis at 460°C for 18 minutes. The fresh biochar used to have water content by mass of 0.84 g/g (Kidane, 2016). Without any further alteration of the biochar properties, it was stored in a plastic bag at room temperature.

This biochar recently obtained a certification as a supplementary soil substance by the Central Institute for Supervising and Testing in Agriculture. The commercial name is "agrouhel" and basic properties are given in Table 1.

***Table 1**. General properties of the tested biochar.*

Characteristics	Value
Burnable matter in dry sample (%)	min. 45.0
Dry matter (%)	min. 60.0
Total carbon content as C in dry matter (%)	min. 45.0
Total nitrogen content as N in dry matter (%)	min. 1.0
Total phosphorus content as P2O5 in dry matter (%)	16
Total potassium content as K2O in dry matter (%)	17
Calcium content as CaO in dry matter (%)	56.3
Magnesium content as MgO in dry matter (%)	6.6
pH	9 – 11.0
Particles <2 mm (%)	min. 40.0
Particles >10 mm (%)	max. 10.0

(Source: http://www.agrouhel.eu/?page_id=8)

In addition, the content of hazardous elements fulfils the limits of law (in mg/kg): cadmium 1, lead 10, mercury 1, arsenic 20, chromium 50, polycyclic aromatic hydrocarbons 20. The recommended field application rate is maximum 2 t of dry matter per ha per 3 years with immediate ploughing under due to the high content of dust. The recommended small-scale rate (for gardening) is 1:100 for mixing with a substrate or compost (www.agrouhel.eu, 2017).

4.3 Repacking the samples

For measurement of the saturated hydraulic conductivity, the method of falling head by employing the Ksat device (UMS GmbH.; further described) was chosen. Soil core samples of volume 250 cm^3 are required for this method. In order to reduce the natural soil heterogeneity and thus the influence of varying porosity to the saturated hydraulic conductivity, homogeneously repacked soil samples were prepared. Measurement ongoing on artificially repacked samples can deal with various problems rising from damaged soil structure. To minimize the difficulties, four methods of repacking the soil samples found in literature were initially tested and the method with the most consistent results was then chosen for all following measurements.

A uniform dry bulk density was kept during preparation of samples within each soil type, however, the target value for dry bulk density of each soil type was chosen based on the typical natural dry bulk density of the soils obtained in situ, which was as follows (Miháliková, M. 2016. pers. comm):

- Silica sand: 1.4 g/cm^3
- Luvisol - Uhříněves: 1.15 g/cm^3
- Chernozem - Suchdol: 1.4 g/cm^3
- Cambisol - Valečov: 1.38 g/cm^3

The dry bulk density of chernozem from Suchdol however, needed to be adjusted to 1.32 g/cm^3 during the repacking procedures based on the excess of soil that did not fit into the Kopecky ring.

In the following methods, each soil sample was prepared separately, including weighing the proper amount of soil, moistening and mixing. For testing the methods, only soil without any biochar was used and only chernozem and luvisol were tested. Two replications of each method, thus 8 rings in total were used for the best method assessment.

4.3.1 Method 1

Sand or soil (air-dry or naturally moist) was mixed with water measured by a cylinder to get an initial water content (10% vol. for sand and 15% vol. for soils), then packed into the core ring in about 0.5 cm layers and gently compacted by a rubber packing tool until all the measured soil was inside and the ring was full. Prepared samples were saturated for 24 hours by capillary forces and approx. 15 min before the measurement the water level of the saturation box was increased to 0.5 cm under the upper edge of the ring to ensure full saturation.

This method was automatically chosen for silica sand as the sand does not create any structure and style of mixing cannot influence the results.

4.3.2 Method 2

Air-dry soil (or naturally moist) was prepared in the required amount and packed into the rings. Care was taken to place each sub-layer in such a way that particle-size fractions and differently sized soil aggregates were distributed as homogeneously as possible. The samples were weighed for initial water content determination and then saturated as described before.

4.3.3 Method 3

Air-dry soil (or naturally moist) was prepared in the required amount and spread into a thin layer on a plastic sheet and gently sprayed by water until moisturized. The soil was then carefully mixed and immediately packed into the rings. Samples were weighed for initial water content determination and then saturated with the same way as in the previous methods.

4.3.4 Method 4

Air-dry soil (or naturally moist) was prepared in the required amount and spread into a thin layer on a plastic sheet, then sprayed by water to be obviously moist and left to free drying for about one hour (see Figure 10). During that time, the water was expected to redistribute from surface of the soil deeper into the aggregates. It was possible to help this happen by breaking some bigger aggregates. The purpose was to simulate naturally wet soil. Then the soil was mixed carefully to avoid clogging and turning to mud and packed to the rings. Samples were weighed for initial water content determination and saturated as described above.

This method was chosen as the most appropriate, as further discussed in chapter 6. This method was applied throughout the rest of the samples with each biochar concentration.

Figure 10. *Chernozem and Luvisol samples are left to dry after being sprayed on plastic sheets before being packed into the Kopecky rings.*

4.4 Sample Labeling

In total, three variants of biochar admixture were tested for each of the four soil types, each variant was carried out at least three times and in addition, each ring was run on the Ksat device at least three times. Thus a labeling system was created to keep track of the running results. The soil types were labeled as explained in Table Table **2.**

__Table 2__. Sample labeling.

Soil type	Locality	Label
Cambisol	Valečov	CA
Chernozem	Suchdol	SU
Luvisol	Uhříněves	UH
Sand	Střeleč	SA

For example, the group of cambisol sample rings with no biochar content was labeled as follows: 0CA1, 0CA2, and 0CA3. Each of these rings was tested 3 times. Thus the resulting data appears as follows: 0CA1_1, 0CA1_2, 0CA1_3, etc. The numbering system was utilized consistently as mentioned before.

4.4.1 Biochar Concentrations

In this study the soil sample cores were subject to the addition of 0% or no biochar admixture (blind control, labeled as 0), 1% dry biochar by mass (labeled as 1), and 0.1% dry biochar by mass admixture (labeled as 2). In the labeling system 0% biochar additions appeared as the first number. As an example, the sand with 0% biochar was labeled 0SA1, while sand with 1% biochar was labeled 1SA1.

The chosen biochar concentrations were based on practical applications to agricultural field environments suggested by previous studies found in literature. The concentration 0.1% or 0.001 g/g (biochar dry matter to air dry soil actually) roughly corresponds to the application rate about 3 t/ha, and the concentration 1% or 0.01 g/g roughly corresponds to the application rate about 30 t/ha, which meets the recommendation of the producer (see chapter 4.2) for field and gardening application, respectively. However, the actual biochar concentration in the field application depends on several factors, mainly the actual depth of ploughing and dry bulk density of the soil, which is changing during the vegetation season. For that reason, the added amount of biochar to different soil types with different proposed bulk densities remained the same. Calculated estimation of the biochar concentrations is given in Table 3.

Table 3. *Calculation of biochar concentrations.*

labeled on samples	1	2
biochar concentration	**1.0%**	**0.1%**
average depth of ploughing (m)	0.22	0.22
1 ha area (m^2)	10000	10000
1 ha ploughing layer soil volume (m^3)	2200	2200
approx. dry bulk density (g/cm^3)	1.3	1.3
corresponding ploughing layer soil mass per 1 ha (kg)	2860000	2860000
biochar application rate (t/ha)	30	3
estimated biochar concentration (g/g)	0.01049	0.00105
mass of dry biochar added to 1 kg of soil (g)	10	1
prepared biochar concentration (g/g)	0.01	0.001

4.4.2 Biochar water content

The biochar concentrations are related to dry matter of the biochar, as it may contain not negligible amount of water. On the other hand, the water content of air-dry soil was around 3% by mass, thus it was neglected. The biochar water content was determined by standard gravimetric method of weighing a moist sample and drying to the constant mass at 105°C. The water content was then calculated according to eq. 4:

$$w = \frac{m_w}{m_s} \qquad \text{(eq. 4)}$$

Where w is water content by mass (g/g), m_w is mass of water (obtained as mass of moist sample minus mass of the dry sample; g), and m_s is mass of the dry sample (g).

The biochar water content was determined as 55% by mass. Knowing that the prepared biochar had 55% water content and it was necessary to calculate the concentrations considering only the dry mass of the biochar another calculation was applied to figure out the proper mass of biochar needed to compensate for the water content. So to obtain 1% biochar concentration in 1 kg of soil it is calculated as 10 + 10 × 0,55 = 15.5 g of biochar to be added. The same factor was applied to the 0.1% concentration. Figure 11 shows the ready biochar before soil admixture.

Figure 11. *Biochar of 55% water content.*

4.4.3 The Ksat Device

The Ksat device (UMS GmbH., Munich, Germany) was used to conduct falling-head experiments to measure the saturated hydraulic conductivity of soil samples based on Equation 1 and calculate according to Equation 2. The measuring device is connected with a computer via USB and the measurements are operated via special software (UMS GmbH, 2013). The K_s value is calculated automatically by the software. Each sample was run on the Ksat device at least three times and the resulting K_s was the average of the three trials. The coefficient of determination is calculated as well and provides information about the quality of fitting the formula (eq. 2) to the registered data. The snapshot of the Ksat software is shown in Appendix 2.

When determining the saturated hydraulic conductivity it is critical that there are no gaps, crevices or cracks in the sample along the direction of percolation. The detail of the measuring dome (where the sample is going to be attached) is displayed on the photo in Appendix 3. The biggest problem is the edge gaps. Soil cores that are tilted during the sampling are likely to have such edge gaps and should be discarded (UMS GmbH, 2013). According to Dirksen (1999) the accuracy of measurements is dependent on the quality and representativeness of the samples themselves. The Ksat device operated in falling head mode is demonstrated in Figure 13. Figure 14 was taken from the laboratory. It shows physical set up of the Ksat machine for the purpose of conducting the falling head measurements.

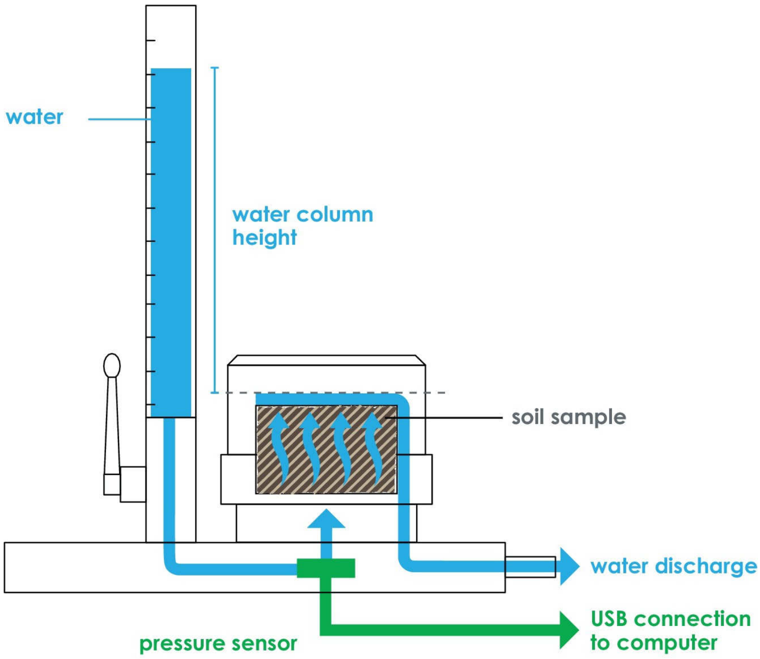

Figure 12. *The scheme of the Ksat device (UMS GmbH, 2013).*

Figure 13. *The Ksat machine ready for a sample measurement (picture taken in the laboratory).*

4.4.4 The effect of temperature on changing the value of K_s

Hydraulic conductivity is a property used to describe the attributes of both soil as porous media and water as the transmitted liquid. Soil characteristics affecting K_s are the total porosity, distribution of pores, and tortuosity. Fluid attributes that affect K_s are density and viscosity (Hillel, 1998). These factors are dependent upon temperature. Theoretically K_s may be separated into two factors: the *intrinsic permeability* of the soil k and *fluidity* of the permeating liquid f. Since fluidity is directly related to density and inversely to viscosity the formula for permeability of a soil matrix is as follows (eq. 5):

$$k = K_s \frac{\eta}{\rho g} \qquad \text{(eq. 5)}$$

Where k is the intrinsic soil permeability (m^2) η is the dynamic viscosity ($N.s/m^2$ or Pa.s), ρ is the fluid density (kg/m^3), and g is the gravitational acceleration (m/s^2). Changes in pressure are naturally occurring at the surface of the earth, however, even through this the density of liquid remains generally constant. Slight changes in water density are usually the result of varying temperatures, solute concentrations, and primarily from changes in viscosity (Hillel, 1998).

In this point of view the temperature at which the K_s readings were taken became very relevant and due to inconsistent temperature in the laboratory during testing it was necessary to normalize the results. The Ksat Operational manual (UMS GmbH, 2013) provides formula fitting changes of dynamic viscosity with temperature (eq. 6).

$$\eta = 0.0007T^2 - 0.0531T + 1.764 \qquad \text{(eq. 6)}$$

Where η is the dynamic viscosity of water (mPa . s) and T is temperature (°C). The Ksat software recalculates the measured K_s value according to a selected reference temperature automatically. Recalculation of hydraulic conductivity based on dynamic viscosity was used e.g. by Levi et al. (1989). However, as the water density is changing with changing temperature as well, rather kinematic viscosity should be used (see eq. 7).

$$\nu = \frac{\eta}{\rho} \qquad \text{(eq. 7)}$$

Where ν is the kinematic viscosity (m^2/s), η is the dynamic viscosity (Pa . s) and ρ is the fluid density (kg/m^3). By application of the formulae e.g. 5 and eq. 7, the proper formula for temperature change corrections was achieved (eq. 8):

$$k = K_{sref} \cdot \nu_{ref} = K_{sT} \cdot \nu_T \mathbf{k} = K_{s\,ref} . \nu_{ref} = K_{s\,T} . \nu_T \qquad \text{(eq. 8)}$$

Where k is the intrinsic soil permeability (m^2), $K_{s\ \mathrm{ref}}$ (m/s) and ν_{ref} (m^2/s) are saturated hydraulic conductivity and kinematic viscosity at reference temperature, respectively, and $K_{s\ \mathrm{T}}$ (m/s) and ν_{T} (m^2/s) are saturated hydraulic conductivity and kinematic viscosity at real measured temperature.

For the actual values of ν the following formula was used (eq. 9; Kučera, 2013):

$$\nu = \frac{1.79 \cdot 10^{-6}}{1 + 0.0337 \cdot T + 0.000221 \cdot T^2} \qquad \text{(eq. 9)}$$

Where T is temperature (°C).

All measurements were recalculated to reference temperature 20°C.

4.5 Statistical Markers

The purpose of statistical analysis is first to recognize the characteristics of collected data in order to determine the validity of values in the scope of the work. Determining these characteristics can prevent the unnecessary inclusion of false data in to the analysis. Once the characteristics of the data are determined and appropriately selected, then the statistical analysis and summarization may be completed using the most valuable data to assure the quality of results (Helsel and Hirsch, 2002).

4.5.1 Coefficient of Determination

The coefficient of determination (R^2) equals to the squared Pearson correlation coefficient R and it is a number that indicates the proportion of the variance in the dependent variable that is predictable from the independent variable(s). R^2 is a statistical measure of how close data is to the fitted regression line and gives information about the goodness of fit of a model. The R^2 value is always between 0 and 1 because it is the percentage of the response variable variation that is explained by a linear model. So 0, or 0% indicates that the model explains none of the variability of the response data around its mean and 1, or 100% indicates that the model explains all the variability of the response data around its mean.

The R^2 value in this falling head test was collected for all measurements and analyzed. Each sample was tested an average of 3 or 4 times, then the values with R^2 less than 0.95 were omitted from statistical analysis.

4.5.2 F-Test

The F-test of equality of variances is one method for finding out if a group of results is statistically significant, meaning that they did not happen by chance but rather have some relevance to the characteristics of those values. The F-test is derived from the regression analysis, and mainly it is used when deciding to accept or reject a null hypothesis which otherwise appears simply as an insignificant outlier (Statistics How To, 2017a).

4.5.3 T-Test

The t-test is likewise derived from the regression analysis but this test determines the statistical significance of a single variable. This is done by comparing two means in terms of difference and determining if that difference could have happened by chance. Thus it is used to judge the likelihood of the data values to repeat (Statistics How To, 2017b).

4.6 Software used

Microsoft Word, Microsoft Excel, UMS Ksat software (UMS GmbH., Munich, Germany), Statistica 13.2 (Dell Inc., USA).

5 Results

Core samples according to Method 4 (described in chapter 4.3.4 and further commented) were prepared to the target dry bulk density (see chapter 4.3) and weighed to determine the initial water content; saturated prior to the measurements of saturated hydraulic conductivity and weighed after the measurement to determine the saturated water content. After that, the soil samples were dried in the oven at 105°C to the constant mass and weighed. The real dry bulk density of each sample was calculated. Particle density of each soil was determined by water pycnometer method (according to standard procedure CEN ISO/TS 17892-3) and used for calculation of soil porosity.

In total, four soil types were used, three biochar concentrations for each of them with minimum three replicates, and each single ring was run on the Ksat device at least three times. The results were registered and statistically analysed.

In addition, the same hydrophysical measurements were conducted for pure biochar as well, in three replicates.

All measurements were carried out in the laboratory of Department of Water Resources, Faculty of Agrobiology, Food and Natural Resources. The average temperature during the measurement was 23.3°C with minimum 20.0°C, maximum 24.5°C and coefficient of variation (CV) 4.6%. All the measured K_s were recalculated to 20°C according to eq. 8.

5.1 Particle Density

The particle size density of each soil was determined by the water pycnometer method and are listed below. Figure 14 shows the pycnometer samples in the laboratory. For biochar determination, ethanol was used as a reference liquid instead of degassed, distilled water.

(1) SA (sand): 2.65 g/cm^3

(2) UH (luvisol): 2.645 g/cm^3

(3) SU (chernozem): 2.635 g/cm^3

(4) CA (cambisol): 2.709 g/cm^3

(5) Pure biochar: 1.097 g/cm^3

Figure 14. *Pycnometers with all soil samples (photo taken in laboratory).*

5.2 The Most Appropriate Packing Method Evaluation

The results of the trial repacking methods applied to the soil samples without biochar admixtures were evaluated either in terms of consistency of the method, either by comparison to K_S field values. The chosen method was the one that provided the best results in terms of the low coefficient of variation (CV) together with the laboratory measured K_S value close to the field value of each given soil. As a reference point, each method was applied to chernozem (Suchdol) and luvisol (Uhříněves) soils. Table 4 displays the results of each method.

Table 4. *The analysis of the repacking method data applied to. Stdev is standard deviation.*

Packing method	M1		M2		M3		M4	
N. of samples	4		4		4		4	
N. of replicates	12		12		12		12	
N. of valid rep.	11		9		10		10	
Sample name	M1SU	M1UH	M2SU	M2UH	M3SU	M3UH	M4SU	M4UH
CV	6.5%	51.1%	58.5%	22.8%	30.9%	51.9%	23.9%	26.4%
Stdev (cm/d)	7.3	493.8	468.7	115.3	68.5	551.5	45.1	550.1
Average K_s (cm/d)	112	966	801	507	222	1062	189	2086
Average K_s (m/s)	1.3E-05	1.1E-04	9.3E-05	5.9E-05	2.6E-05	1.2E-04	2.2E-05	2.4E-04

Packing methods are denoted as M1, M2, M3 and M4. Number of valid replicates means shows how many measurements were omitted due to low R^2 as further described.

The K_S field values for these are 271 cm/d (Krkavcova, 2010) and 2044 cm/d (Mihalikova, M. 2016. pers. comm.) respectively. Method 4 shows the lowest CV values similarly for both soils and the saturated hydraulic conductivity most similar to the field values.

5.3 The Effect of Biochar on Basic Soil Physical Properties

The aim of the work was to maintain the constant dry bulk density in order to focus on the effect of biochar on K_S. Figure 15 shows the actual dry bulk density of the measured samples with comparison to target dry bulk density. There are some small differences, however, the differences are statistically insignificant on the significance level p = 0.05 as demonstrated in Table 5 by t-test for independent samples. These differences were caused probably by two main factors, firstly by small soil losses during preparation of the sample (some soil remained on the plastic sheet, bowl and packing tools, see Figure 10) and secondly, some soil particles could be flown out during the repeated falling head experiment.

The same table shows also that there is no difference between bulk densities in soils with different biochar concentrations. Thus, biochar admixture did not show any effect on dry bulk density in this study. However, this observation should not be generalized as the samples were artificialy repacked and measured immediately.

The dry bulk density of pure biochar was determined as 0.19 g/cm^3 and thus porosity was calculated as 83%. This value includes the intrinsic porosity of the biochar particles as well as the pores between the particles which may be affected by different levels of compaction.

The calculated porosity of the tested soil samples was compared with the measured value of saturated water content. The degree of saturation can be calculated as ratio of volumetric water content and porosity. Its value can be maximum 100% (in non-swelling soils) and shows the ratio of pores filled by water to all pores. The maximum degree of saturation is for saturated water content. As can be seen from Figure 16, the biggest maximum degree of saturation was measured in cambisol, while the lowest in luvisol. The degree od saturation of pure biochar was 82%. This rather low value for biochar can be explained by presence of non-capillary pores between the biochar particles which were drained very quickly.

Figure 15. *Actual and target bulk densities in all tested variants of biochar admixtures.*

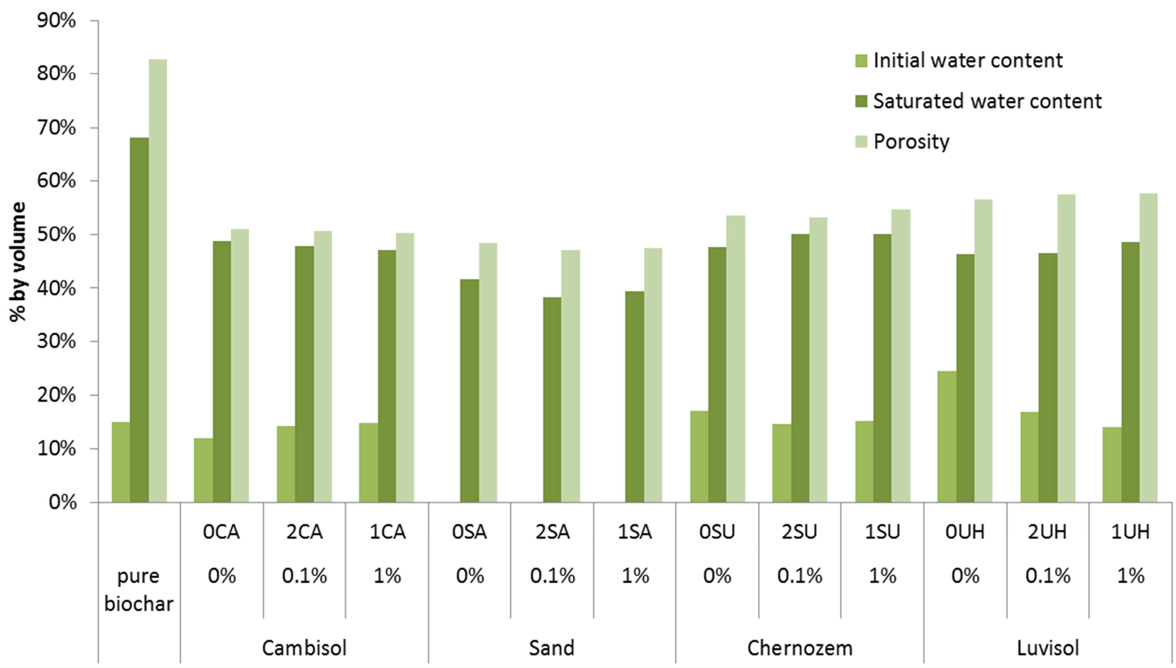

Figure 16. *Initial water content, Saturated water content and Porosity of all tested variants of biochar admixtures.*

Table 5. Differences between bulk densities in all tested variants of biochar admixtures carried out by t-test for independent samples.

	biochar	0CA	1CA	2CA	0SA	1SA	2SA	0SU	1SU	2SU	0UH	1UH
biochar	1.000											
0CA	0.000	1.000										
1CA	0.000	0.364	1.000									
2CA	0.000	0.591	0.680	1.000								
0SA	0.000	0.063	0.124	0.105	1.000							
1SA	0.000	0.006	0.001	0.005	0.133	1.000						
2SA	0.000	0.004	0.001	0.003	0.064	0.093	1.000					
0SU	0.000	0.014	0.003	0.006	0.001	0.000	0.000	1.000				
1SU	0.000	0.011	0.003	0.005	0.001	0.000	0.000	0.431	1.000			
2SU	0.000	0.014	0.002	0.005	0.000	0.000	0.000	0.540	0.200	1.000		
0UH	0.000	0.003	0.001	0.002	0.000	0.000	0.000	0.057	0.196	0.024	1.000	
1UH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.005	0.028	0.001	0.254	1.000
2UH	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.007	0.037	0.001	0.324	0.675

5.4 Avoiding outliers from K_s measured values

After saturation, samples were attached to the Ksat device one by one and measured 3-5 times. The resulting K_s value should represent the average of the replicates, however, some outlying values occurred and these were not included into the average. The Ksat software computes K_s value directly by fitting the curve of the decreasing water level in the byreth over time using the formula for falling head setup (eq. 2). The coefficient of determination for the fit is calculated as well. The outliers were identified by low determination coefficient. The lowest R^2 was 0.733, but in general, all values less than 0.95 were considered outliers, which was proven by the significant difference of those replicates from others. A total of 182 replicates were measured. From this number, 23 replicates were identified as outliers; 14 from sand sample measurements, 8 in the measurements for choosing the repacking method and only 1 in the measurement of a sample with soil.

5.5 Results of Saturated Hydraulic Conductivity Test

Table 6 shows the K_s measurement results of sand, cambisol, chernozem, and luvisol in order of each applied concentration plus biochar itself with the basic descriptive statistics. By looking at the under the average K_s column and matching it with the rows of each soil+biochar concentration it is observable the correlation of biochar admixture and its effect on the soil type it is applied to. Especially in the case of the chernozem, which is directly correlated with the increasing content of biochar. The minimum and maximum values along with the CV display the stability of the measurement and thus of the soil under the influence of biochar admixture. Overall, the higher contents for every soil display smaller deviations and specifically in sand and cambisols, the coefficient of variance decreased with greater admixture. In chernozem for example, the standard deviation decreased but much more gradually.

Table 6. *The results of the K_s data for all variants of biochar admixtures.*

Conc. of biochar (%)	Soil	No. of samples	No. of replicates (total)	No. of replicates (valid only)	min (cm/d)	max (cm/d)	CV (%)	average (cm/d)	average (m/s)
100	Biochar	3	9	9	1461.5	1858.1	7.8	1683.6	1.95E-04
0	0SA	5	17	9	626.4	979.4	17.5	743.4	8.60E-05
0.1	2SA	4	12	10	364.8	624.3	12.9	538.4	6.23E-05
1	1SA	4	12	8	474.0	540.7	4.4	509.9	5.90E-05
0	0CA	3	9	9	45.5	154.4	42.8	77.1	8.92E-06
0.1	2CA	3	9	9	30.5	38.1	8.2	33.7	3.90E-06
1	1CA	3	9	9	26.9	37.0	10.7	31.2	3.61E-06
0	0SU	3	9	9	68.0	130.1	20.6	101.1	1.17E-05
0.1	2SU	3	9	9	134.4	222.5	16.8	182.3	2.11E-05
1	1SU	3	9	9	193.4	314.8	15.0	245.5	2.84E-05
0	0UH	3	12	12	678.8	1448.7	23.7	1025.5	1.19E-04
0.1	2UH	3	9	8	1193.6	5626.4	55.7	2598.7	3.01E-04
1	1UH	3	9	9	557.2	1389.8	29.4	1013.8	1.17E-04

In order to better describe the effect of biochar admixtures to each soil type, firstly the differences between the K_s of the soils themselves were observed by performing the F-test of equality of variances (see Table 7). The F value is ratio between the variances s_1^2 and s_2^2 where $s_1^2 > s_2^2$. If F is higher than the F-critical value, the two variences are statistically different on the significance level p (which is marked by red color in the table). The test showed that the tested soils are different from each other on the significance level p = 0.05 in terms of saturated hydraulic conductivity (except of cambisol and chernozem, which showed no significant difference in their variances). On the other hand, F-test performed on K_s variances for different biochar concentrations (Table 8) showed no significant difference between the variances in both biochar admixtures in cambisol, between luvisol with no biochar and 1% of biochar, and between all chernozem concentration. It shows the effect of stabilizing the K_s measurements in cambisol and no effect in this case for chernozem.

Table 7. *F-test of equality of variances (s^2) between the K_s in different soil types.*

s_1^2	s_2^2	F	p	F critical value
sand	cambisol	15.614	0.00039626	3.438
cambisol	chernozem	2.520	0.10634473	3.438
luvisol	cambisol	52.764	3.0892E-06	3.313
sand	chernozem	39.349	1.2435E-05	3.438
luvisol	sand	3.379	0.04740836	3.313
luvisol	chernozem	132.969	8.1533E-08	3.313

Table 8. *F-test of equality of variances (s^2) between the K_s in different biochar concentrations.*

s_1^2	s_2^2	F	p	F critical value
0CA	1CA	97.871	3.5744E-07	3.438
0CA	2CA	141.444	8.3589E-08	3.438
1CA	2CA	1.445	0.30732796	3.438
0SA	1SA	32.918	7.0466E-05	3.726
0SA	2SA	3.547	0.038419	3.230
2SA	1SA	9.281	0.00385751	3.677
1SU	0SU	3.117	0.06419778	3.438
2SU	0SU	2.178	0.14577649	3.438
1SU	2SU	1.431	0.31215816	3.438
1UH	0UH	1.550	0.2452557	2.948
2UH	0UH	37.080	8.6483E-07	3.012
2UH	1UH	23.922	9.2416E-05	3.500

After performing statistical analysis of all the data for this experiment all figures were taken into account to formulate a layout of significant differences between variable soil types and the effects of the levels of biochar admixture.

Figure 17 displays the statistical averages of the final results and the lower and upper quartiles to determine the consistency of the soils as effected by biochar throughout the experiment.

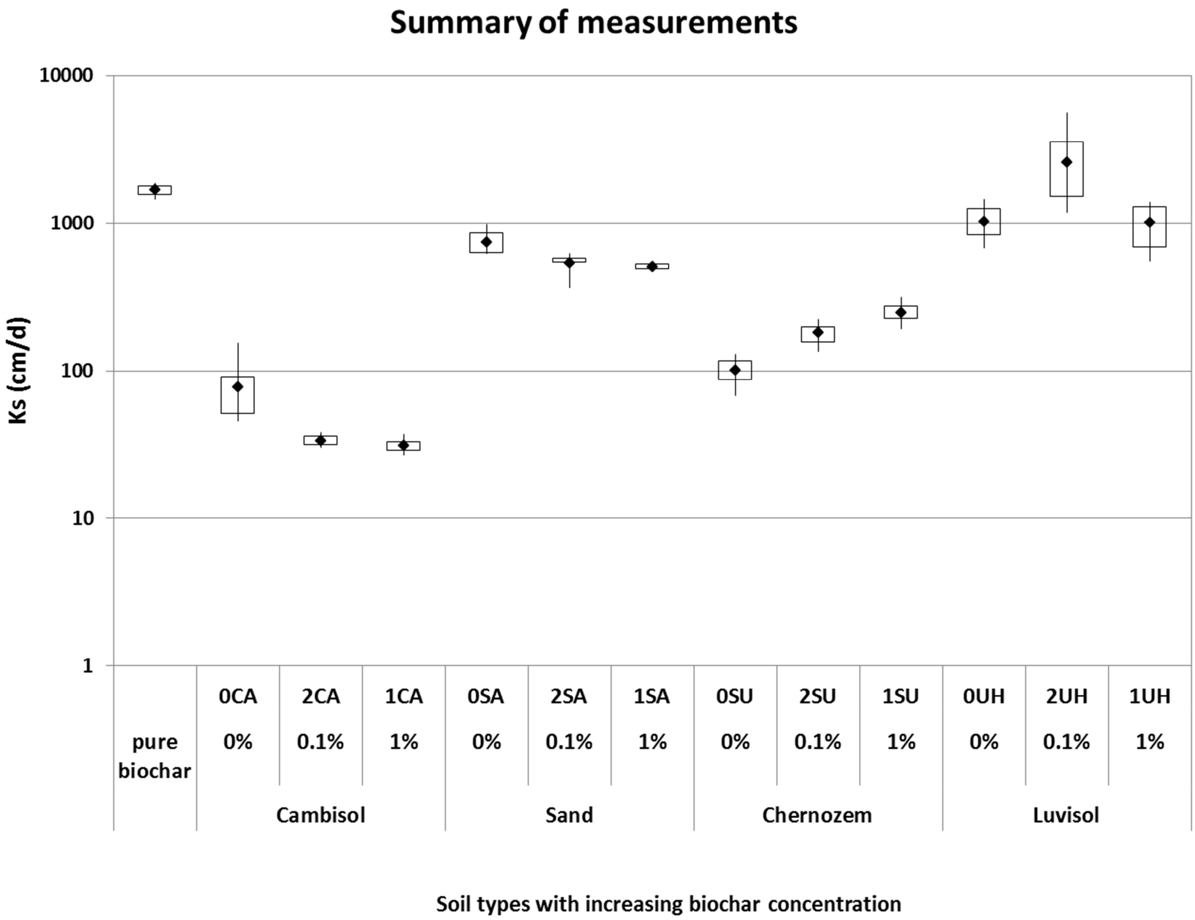

Figure 17*. Graphical overview of the measured results of K_s in logarithmic scale. Black dot is mean, box boundaries are lower and upper quartile and bars are minumum and maximum values of all valid measurements for each particular soil type and biochar concentration.*

From this data it is important to comment on the increasing stability of measured K_s values under the influence of increasing admixtures. This is most significant in cambisol and sand samples, where the differences between the maximum and minimum and upper and lower quartiles decrease. The influence of biochar decreases the value of K_s for these samples. (Appendix 4 provides a more detailed visual reference about how the biochar affects the K_s of these soils). Although the differences between the upper and lower quartiles did not change too much in the chernozem samples, the effect of biochar is clearly visible. The relationship between the percentage of biochar content and K_s is direct. The chernozem, which is already a stable well-structured fertile soil, increases its K_s value with the content from 0% to 0.1% and 1% gradually. The luvisol samples show inconsistent and highly variable results, however, the effect of biochar is significant.

What has been made clear from this experiment is the different effects of biochar as a material on different soil types. Greater and smaller application effect each soil in a specific manner, whether the changes are observed in the increasing/decreasing values of K_s or the consistency of measurement there is a definitive relationship that each soil type has with the admixture of biochar.

Performing the t-test for independent samples proved the differences. The t-test matrix, Table 9, was built to compare the differences between the effects of specific biochar concentrations on a soil type.

Table 9. *T-test matrix for mean K_s values of all variants of biochar admixtures.*

	biochar	0CA	1CA	2CA	0SA	1SA	2SA	0SU	1SU	2SU	0UH	1UH
biochar	1.000											
0CA	0.000	1.000										
1CA	0.000	0.001	1.000									
2CA	0.000	0.002	0.120	1.000								
0SA	0.000	0.000	0.000	0.000	1.000							
1SA	0.000	0.000	0.000	0.000	0.000	1.000						
2SA	0.000	0.000	0.000	0.000	0.001	0.310	1.000					
0SU	0.000	0.101	0.000	0.000	0.000	0.000	0.000	1.000				
1SU	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	1.000			
2SU	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.002	1.000		
0UH	0.000	0.000	0.000	0.000	0.007	0.000	0.000	0.000	0.000	0.000	1.000	
1UH	0.000	0.000	0.000	0.000	0.032	0.000	0.000	0.000	0.000	0.000	0.926	1.000
2UH	0.097	0.000	0.000	0.000	0.003	0.002	0.001	0.000	0.000	0.000	0.003	0.009

Using this matrix one can derive from it which soils exhibited a significant change in K_s between specific intervals i.e., 0%-1%, 0.1%-1%. To do this one must trace specific sample of interest from the row, and the sample desired to compare it to, down to the meeting point in the middle of the table. The significant changes are represented by the red color while the black numbers mean there is no significant difference between samples.

To thoroughly compare these results to practical applications it is clear that the effect that biochar has on sands and cambisols is very significant and it is obvious by the decrease in K_s and the standard deviation of the measurement that these soils benefit from biochar in terms of establishing a more stable structure with the help of minimal application. Thus, to convert the concentration of 0.1% by mass to field scale, applying 3 t/ha of biochar to sands or cambisols would be an ample amendment developing greater quality of the structure and water infiltration capability. As for the chernozem and luvisol that are well structured and contain higher ratios of clay particles, they respond to the effect of biochars more gradually.

6 Discussion

6.1 Repacking Methods Evaluation

There is no standard method for repacking the core samples, as it is used only in specific cases, otherwise the undisturbed soil samples taken in the field are commonly and preferrably used. Method 4 was chosen as the most appropriate because it provided the most consistent results closest to the field values of saturated hydraulic conductivity in addition to properly maintaining the target dry bulk density of each soil. This method is closest to the standard Proctor test as described in chapter 3.5.1.

The method of Mohawesh et al. (2017) to prepare soil samples for repacking and saturation were similar to this experiment as they homogenized the all soils on a constant sieve (2 mm) and then wetted them by means of spraying and mixing to achieve a water content of about 25-30%. After wetting the samples to the desired water content, they placed them in a plastic bag and refrigerated them, firstly to maintain water content, and secondly to prevent the development of microbial life that can further affect the hydraulic properties of the soil. That is different from the procedures of this experiment because here the samples were left to dry for one hour after being totally wetted on the surface level, this approach was used to simulate the natural conditions of wet soil in situ. In this study, the initial water content of the soil samples only (sand excluded since Method 1 was used for repacking) varied between 9 and 27% by volume, with average 16% by volume and CV 23%, see Figure 16. Higher water contents would certainly cause turning the soil to mud. Attention should be paid to obtaining as low variability as possible in initial water content, because it may affect the actual dry bulk density value with direct relationship. However, no significant difference was observed between the bulk densities (Table 5) in this study, thus the range of the initial water content was acceptable.

The method of repacking according to Mohawesh et al. (2017) was more efficient because, unlike the Proctor method of packing and the method used for this experiment, they implemented the use of a uniaxial compression device. This device compresses the soil into a 250 cm^3 metallic ring from both sides. This is beneficial because compacting both sides of the soil evenly within the ring assures that the desired bulk density has been achieved at all levels of the soil sample, at least more so than just compacting one side of the sample. Furthermore, repacking using the uniaxial device can produce more consistent measurements on the Ksat device machine, since the flow of water through the sample starts from the bottom up.

The homogenized soil samples of Mohawesh et al. (2017) showed a decrease in soil hydraulic conductivity. Opposite observation was made within this study, K_s increased when compared with the field values. However, this trend depends strongly on the level of compaction, thus the reported trend cannot be generalized. Actually, the bulk density in the discussed study was much higher than here.

6.2 Ksat Measurement Evaluation

The Ksat measurements provided useful insight into the effects of biochar on different soil types and textures/structures. Well-structured soils with higher ratio of fine soil particles such as chernozem and luvisol exhibit an increase in K_s due to biochar addition while light, poorly structured soil types such as cambisol and sand exhibit a decrease in K_s, and along with the slowing of water flow, benefit from stabilizing the porous system due to increasing the organic matter content (see Table 8 and

Figure 17). These observations are supported by other studies as well. Barnes et al. (2014) in the laboratory the effect that biochar has on the K_s and unsaturated hydraulic conductivity (K) of sands, clay-rich soils, and organic soils. They found that the K decreased in sand by 92% and in organic soils by 67%, but increased drastically by 328% in clay-rich soils. An interesting fact from their study is that with the addition of biochar the K for sand decreased even though it became less dense and more porous than it was without the biochar.

In addition, they ran column experiments to determine the effect of 10% biochar by mass on the K_s of all soils. This concentration represented a field value of 133 t/ha. That was a much higher amendment rate than in this experiment where the biggest ratio was 1% by mass representing 30 t/ha. For field practices the application of 133 t/ha is largely impractical, however, for the purpose of testing the effect of biochar on a greater scale it ensured the quality of their experiment.

As a part of an experiment testing the physical properties of biochar and soil mixtures performed by Kidane (2016), the Ksat machine was also utilized to measure K_s by means of a falling head experiment. He was testing the same chernozem, cambisol, and silica sand used in this experiment with the same concentration of biochar to the samples and the same biochar itself. Sample preparation was carried out similarly except in his experiment there was no emphasis on maintaining a specific bulk density for the soil types, thus there was no packing method carried out. In his experiment, the samples were simply poured into the Kopecky rings and saturated by capillary rise for 24 hours, relying on wetting and gravity to cause spontaneous collapse of the soil as a means of compaction. This differed greatly from the way this experiment was repeated with attention to bulk density, proper wetting and compaction procedures. What was similar about the process was the capillary saturation step and the immersion into water before the Ksat measurement.

By examining the changes in K_s in his experiment and comparing the standard deviations of each repetition sample there was a clear and observable reaction of chernozem, cambisol, and sand to the biochar however; there was no noticeable trend or correlation between the concentrations. The greatest response to the biochar was that of the well-structured chernozem, which poured into the sample ring and saturated over night, retained its natural aggregate structure and pore distribution perfect for inducing water flow even without the biochar. The effects of introducing biochar into soil are visible, although without maintaining a desired bulk density for each individual soil it is difficult to see the true relationship between higher and lower concentrations.

By comparing this experiment to that of Kidane (2016) has been learned that having given specific care to maintaining the desired bulk density of each soil made it possible to determine a positive/negative relationship between K_s and biochar.

As a finding of this study it can be said that the effects of biochar on well-structured soils are much less dramatic than on the light and loose structures of sands and cambisols. As the response of these soils may vary depending on rate of biochar application, it would have to be suggested that by practical applications and experience the right amount of biochar per ha could be determined, be it 3 t/ha or 30 t/ha. This is because the soils are well formed and benefit from the biochar through increased flow of water through saturated pores, so based on the desired effect the right concentration can be decide on.

A field study was conducted by Huislová and Čechmánková (2017) using the same biochar as in this laboratory study. Comparing two variants, without biochar and with biochar (unfortunately the rate of application was not given), they conducted two-year experiment on soil classified as haplic cambisol of silt texture, with quite low soil organic matter content (Kadlec et al., 2012). Improvement of soil structure was proven on increased soil aggregate stability. Value of K_s in the variant with biochar increased to $1.17 \cdot 10^{-4}$ m/s as compared with the variant without biochar $5.89 \cdot 10^{-5}$ m/s. This result is in agreement with this study, where the K_s value on cambisol increased as well for the variants with biochar.

6.3 Possible sources of errors

All experimental parts were conducted with the best care and keeping on the methodology, however, some inconsistent results and outliers occurred during the whole amount of measurement. Outliers occuring during the falling head measurement were identified by lower R^2 value as described in chapter 5.4. Outliers in sand samples can be explained either by lack of experience because the sand was measured first, or by very low levels or no cohesion between the sand particles. Probably a lower pressure head should be applied for measurement to prevent this sitiuation. Outliers in the measurements for choosing the repacking method can be explained by non-complete saturation of the samples before the measurement that occurred as an operational mistake.

Furthermore, the luvisol samples show inconsistent and highly variable results. It was already mentioned that preparation of homogenized soil samples depend on several factors and it is not easy to correctly deal with all of them. Specifically in the case of the Uhříněves' luvisol, which during the sample packing in some cases did not fill the volume of the Kopecky ring to the top. This could be caused either by underestimated dry bulk density, either by higher level of campaction induced by higher initial water content compared to other soil types, which can be observed on Figure 16. As the samples were treated equally, the probable reason for higher initial water content in luvisol samples might be higher actual water content in the soil stored, as this soil was brought from the field as the last one. It can be recommended to pay better attention to the actual soil water content used for soil homogenization, and alternatively increase the target dry bulk density. An opposite situation occurred with the cambisol sample, which during the packing of the no biochar concentration, had overfilled the ring and left over extra soil. This was likely the result of improper wetting applications during preparation and thus difficult compaction.

Measurement of Ks on luvisol samples was probably influenced by the mentioned findings, as the Ksat device is highly susceptible to gaps along the direction of percolation as described in chapter 4.4.3. In the view of overal statistical analyses and comparison, the sample 2UH3 should be taken as an outlier. It is the sample the far highest K_s value measured. All the luvisol samples are troubled by the problem of unreliable measurements so no important and sure comments can be made, although the biochar certainly altered the K_s of the luvisol and the effect is visible. Improving upon this measurement may yield better results.

7 Conclusions

This study focused on the effect of two different biochar concentrations on the K_s of four different soil types. By maintaining the bulk density of each soil type and carefully adhering to the control variables of the experiment has provided reliable data on the mechanism of biochar within soil. It was hypothesized that the addition of biochar to soils will enhance the infiltration capacity of the tested soils. This hypothesis was proved however the exact effects can be seperated into two catergories.

Firstly, the biochar admixture decreased the saturated hydraulic conductivity of silica sand and cambisol. Light soils such as these are more vulnerable to drought and nutrient leaching. This projects that in the case on these soils the biochar slows down the loss of water in the saturated samples.

The opposite effect was the reaction of well-structured soils with finer soil textures, such as chernozem and luvisol that exhibited an increase in K_s. Although some statistical errors detected that the K_s values for luvisol are unreliable and would need adjustment of bulk density and repetition of measurements.

It was also hypothesized that the increase in biochar admixture will increase the effects on saturated hydraulic conductivity. This hypothesis was not confirmed for the light soils because the K_s values did not differ significantly between the two tested concentrations. This is actually a positive result because it means it is not necessary to apply large quantities of biochar above the financial limit of farmers in order to gain the beneficial effects of biochar. A moderate, low-cost addition of 3 t/ha (0.1% by mass) to fields would greatly improve the soil quality.

In the case of chernozem the hypothesis was proven true. The rising biochar concentrations increased the K_s value of the soil. This effect was not observable in the case of luvisol for the reasons mentioned above. However, the results gained attest to the fact that well-structured soils react very well to biochar since it greatly helps the flow rate of water through saturated pores. For agriculture this is an excellent property. For field application, it would be beneficial to further determine the proper concentration according to the needs of the soil.

Based on the results, the objectives of the thesis were fulfilled.

This study tested the immediate effects of biochar applications to soil under controlled laboratory conditions. Another factor to take into consideration for future studies, would be the long-term soil enhancing qualities of biochar after its application to various field conditions. Achieving reliable data about this can mark the quality and efficiency of biochar as a product and expand its economic viability.

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9 Appendices

Appendix 1. Particle size distribution of silica sand used for experiments.

SKLOPÍSEK STŘELEČ
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V.A.T. ID: CZ44795688 | Registered at the District Court in Hradec Králové,
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Banking services: ČSOB Bratislava, a.s.,
IBAN SK81 7500 0000 0000 2575 6453 BIC: CEKOSKBX
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ST 56 *SportTop* - Sand for Sport Surfaces

ST 56 *SportTop* is useful for equestrian use as it is predominately fine and very fine sand. Therefore giving suitable stability for this application.

Rufford
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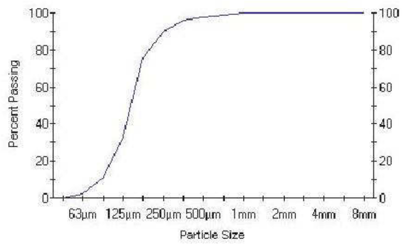
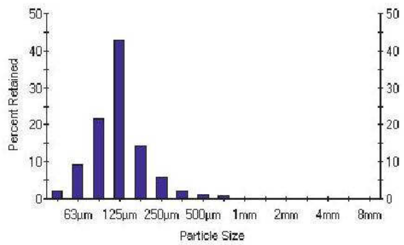




Category	Diameter (mm)	% Retained
Stones	>8	0,0
Coarse Gravel	8 - 4	0,0
Fine Gravel	4 - 2	0,0
Very Coarse Sand	2 - 1	0,0
Coarse Sand	1,0 - 0,5	2,1
Medium Sand	0,5 - 0,25	8,0
Fine Sand	0,25 - 0,125	56,9
Very Find Sand	0,125 - 0,063	30,8

Microns	% Passing	% Retained
8000	100,0	0,0
5600	100,0	0,0
4000	100,0	0,0
2800	100,0	0,0
2000	100,0	0,0
1400	100,0	0,0
1000	100,0	0,0
710	99,9	1,0
500	97,9	1,1
355	95,9	2,0
250	89,9	6,0
180	75,8	14,1
125	33,0	42,8
90	11,3	21,7
63	2,2	9,1
Pan	0,0	2,2

150 µm % Passing	54,9
125 - 150 µm % Retained	21,9
150 - 250 µm % Retained	35,0

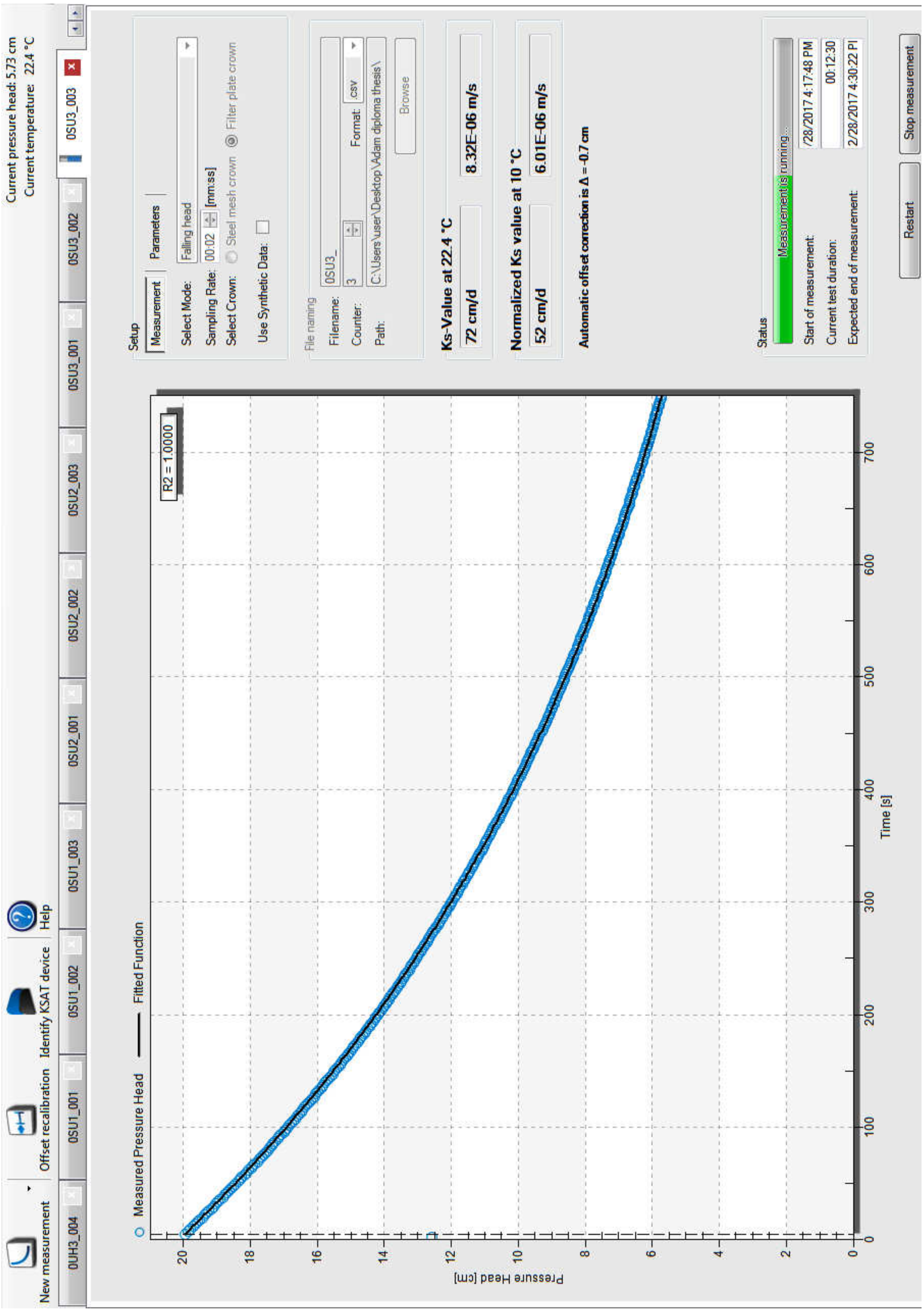
D eff (µm)	109
Total Porosity (%)	37,3
Percolation (mm/h)	143
Critical Tension (mm)	657

D Values		
D0	(µm)	-
D5	(µm)	71
D10	(µm)	85
D15	(µm)	96
D20	(µm)	105
D50	(µm)	143
D60	(µm)	155
D85	(µm)	209
D90	(µm)	251
D95	(µm)	326
D100	(µm)	986
D90 / D10		2,9

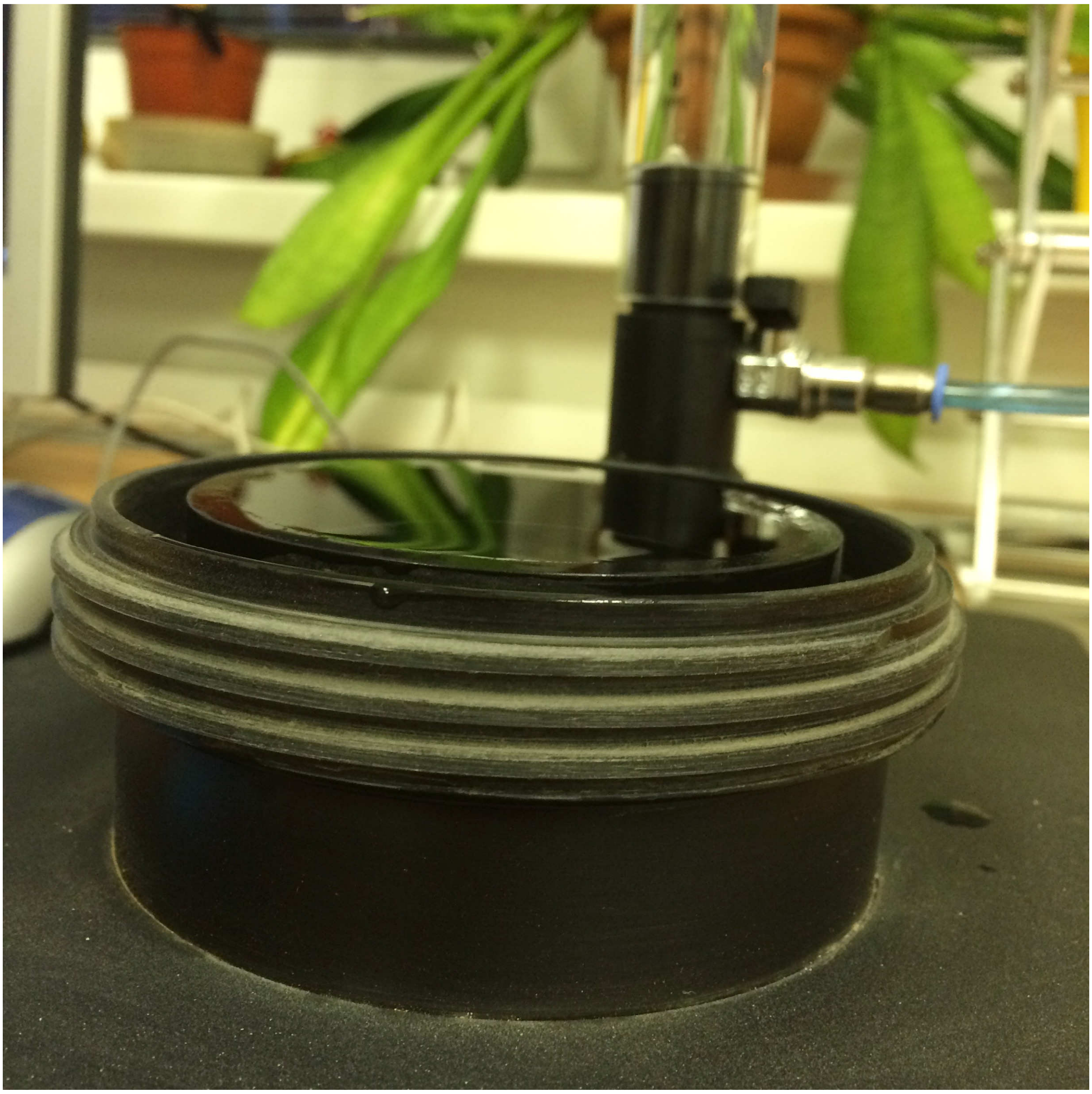
CATALOGUE OF SPORT SANDS 2013

(Source: http://www.glassand.eu/GB/files/Cataloguesporttop.pdf)

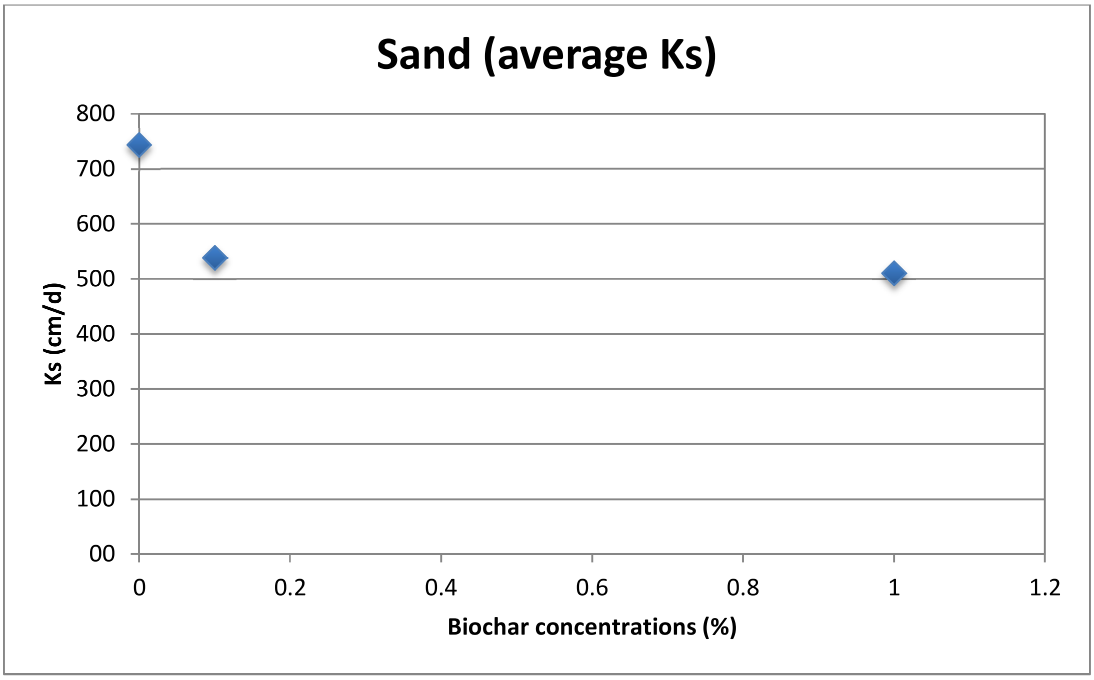
Appendix 2. Snapshot of running UMS Ksat software.

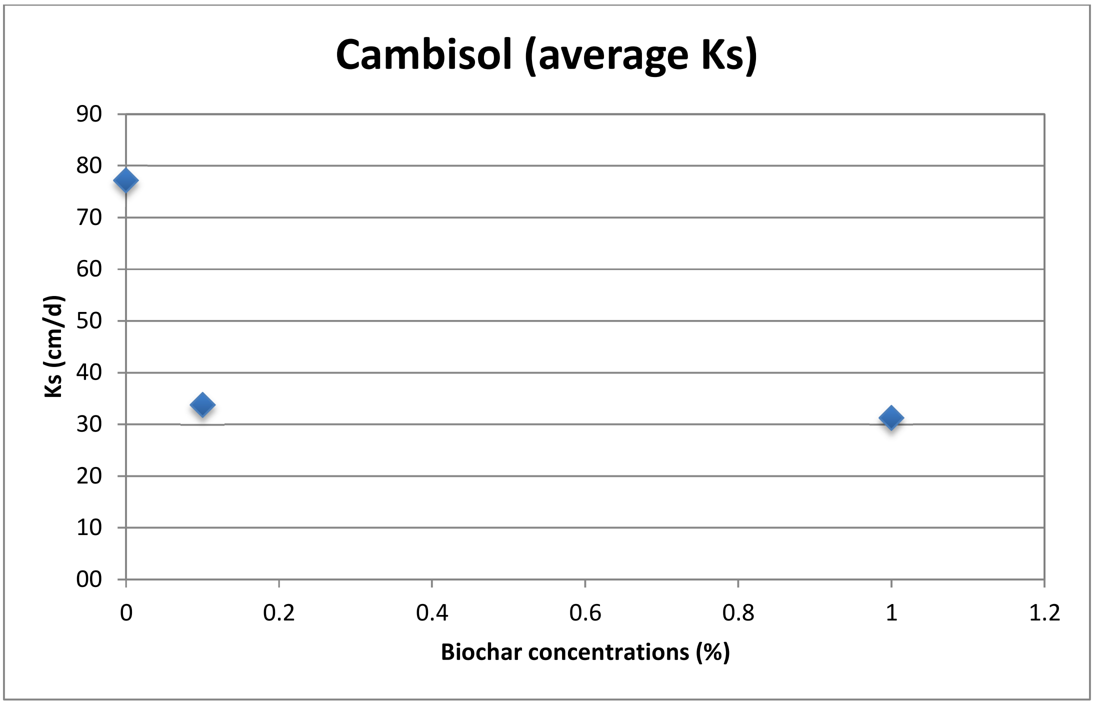


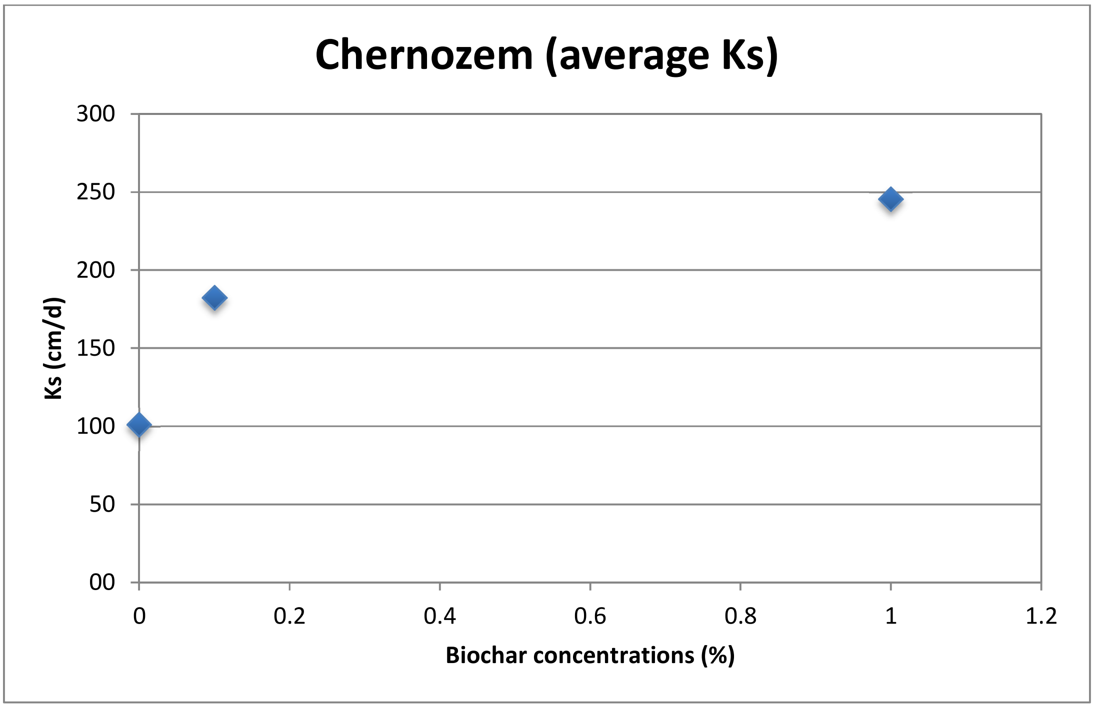
Appendix 3. Detail of the measuring dome on the Ksat device.

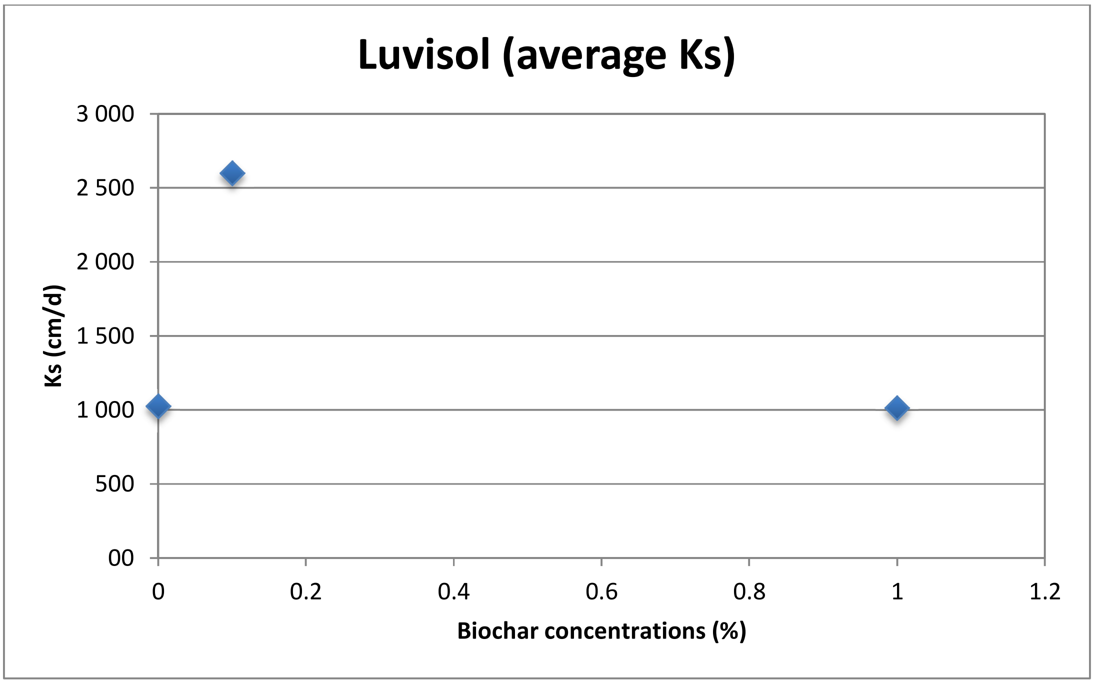


Appendix 4. Relationship of K_s to biochar concentration in soils.






Chernozem (average Ks)
Ks (cm/d)
300
250
200
150
100
50
00
0
0.2
0.4
0.6
0.8
1
1.2
Biochar concentrations (%)


Luvisol (average Ks)
Ks (cm/d)
3 000
2 500
2 000
1 500
1 000
500
00
0
0.2
0.4
0.6
0.8
1
1.2
Biochar concentrations (%)