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A meta-analysis on biochar's effects on soil water properties – new insights and future research challenges

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Abstract

Biochar can significantly alter water relations in soil and therefore, can play an important part in increasing the resilience of agricultural systems to drought conditions. To enable matching of biochar to soil constraints and application needs, a thorough understanding of the impact of biochar properties on relevant soil parameters is necessary. This meta-analysis of the available literature for the first time quantitatively assess the effect of not just biochar application, but different biochar properties on the full sets of key soil hydraulic parameters, i.e., the available water content (AWC), saturated hydraulic conductivity (K_{sat}), field capacity (FC), permanent wilting point (PWP) and total porosity (TP). The review shows that biochar increased soil water retention and decreased K_{sat} in sandy soils and increased K_{sat} and hence decreased runoff in clayey soils. On average, regardless of soil type, biochar application increased AWC (28.5%), FC (20.4%), PWP (16.7%) and TP (9.1%), while it reduced K_{sat} (38.7%) and BD (0.8%). Biochar was most effective in improving soil water properties in coarse-textured soils with application rates between 30 – 70 t/ha. The key factors influencing biochar performance were particle size, specific surface area and porosity indicating that both soil-biochar inter-particle and biochar intra-particle pores are important factors. To achieve optimum water relations in sandy soils (>60% sand and <20% clay), biochar with a small particle size (<2 mm) and high specific surface area and porosity should be applied. In clayey soil (>50% clay), <30 t/ha of a high surface area biochar is ideal.

Keywords: Pyrolysis condition, soil texture, particle size, available water capacity, hydraulic conductivity.

1. Introduction

As a key soil hydraulic property that controls soil management and functioning in ecosystems, soil water retention is crucial for agriculture and the ecosystem. It is important for nutrient delivery to plant and overall crop productivity. About 99% of food for human consumption comes from land (FAO, 2003) and as climate change and population growth (expected world population of 9.2 billion by 2050 (U.N. Population Division, 2008)) have been predicted to limit water supply, especially in arid regions (Niang, 2014), severe food shortages are likely. Over the past 100 years, global mean surface air temperatures have risen by more than 0.5°C (Niang, 2014) with consequential implications for soil water availability. A rise in temperature and decrease in atmospheric precipitation would increase the soil evapotranspiration rate and lead to a decrease in soil water infiltration, storage and plant water supply, which would increase drought sensitivity (Varallyay, 2010; Karmakar et al., 2016). Using the IPCC climate estimates for all climate scenarios up until 2050, some authors have projected a decreasing trend in soil water availability (Komuscu et al., 1998; Holsten et al., 2009). Therefore, solutions addressing the issue of soil water retention are urgently needed. Recent studies have highlighted biochar as a promising tool for increasing the soil moisture content (Basso et al. 2013; Kameyama et al. 2019; Lim et al. 2016; Liu et al. 2017).

Biochar is a carbon-rich solid product of thermochemical conversion of organic matter under oxygen limited conditions, known as pyrolysis. Due to its molecular configuration (strongly bonded carbon atoms), biochar is chemically and biologically more stable than its parent material, making it more difficult to break down. This means that it can remain stable in soil for hundreds to thousands of years (Krull et al., 2006). Due to its recalcitrance in soil, biochar has been proposed as a tool for climate change mitigation and was mentioned in the latest IPCC special report (Rogeli et al., 2018). Many studies have focused on biochar's potential to increase carbon sequestration in soil (Fidel et al., 2019; Yadav et al., 2017), as well as its other potential co-benefits, such as its ability to improve soil physical properties (Herath et al., 2013), chemical properties (Syuhada et al., 2016), fertility and crop yield (Cornelissen et al., 2018; Glaser et al., 2001).

The use of biochar as a soil amendment to increase/maintain soil water content is not only important for agricultural production but also important for functional ecosystems. With regards to crop yields especially in arid regions, biochar can play an important role in combating water scarcity which threatens global food security (Rijsberman, 2006). In terms of runoff and erosion control, biochar can help improve saturated hydraulic conductivity (K_{sat}) and infiltration rate especially in soils with high clay content thereby controlling erosion, flooding and pollution of streams (Li et al., 2018; Lim et al., 2016; Obia et al., 2018). K_{sat} is the ease of flow of water through the soil when it is saturated and it is important for drainage, groundwater, flooding and contamination studies (Kirkham, 2005; Lu, 2015). Most studies show that biochar application increases soil water retention especially in sandy soils (Basso et al., 2013; Mollinedo et al., 2015; Vitkova, et al., 2017), which has generally been attributed to an increase in soil micro-porosity and the highly porous structure of biochar. Conversely, some studies have also showed that biochar had no effect on soil moisture content. Hardie et al. (2014) reported that 30 months after biochar incorporation in a sandy loam, no significant effect was observed on soil moisture content at various tensions (measurement of the amount of energy needed to move water in the soil – further explained in section 2.1). The variation in results from different studies, however, could be attributed to differences in experimental condition, soil texture, application rate, and biochar type.

Some papers have reviewed the effect of biochar on soil physical and hydraulic properties (Blanco-Canqui, 2017) and its effect on plant available water with respect to crop yield responses (Atkinson, 2018). Some studies have done meta-analysis focused on effect of biochar on soil water retention (Omondi et al., 2016; Razzaghi et al., 2019). Omondi et al., 2016 assessed the effect of biochar on selected physical properties (AWC and K_{sat} inclusive), while Razzaghi et al., focused on FC, AWC and PWP considering the biochar carbon added to the soil as well. However, the variations of biochar effects on soil properties were only estimated based on feedstock and pyrolysis temperature (imprecise) without investigating biochar properties that contribute to improved water relations in soil. This knowledge is essential to produce biochars optimised for improving soil-water properties. In addition, the study by Omondi et al. (2016) was limited to effects on available water content and saturated hydraulic conductivity. Information on the soil moisture content at various tensions were not included in the study. Besides available water content this includes, field capacity and permanent wilting point, which are all important for regulating biological and chemical processes in soil, crop growth and productivity and scheduling irrigation (Huntington, 2010; Sparling and West, 1989). This study aims to quantify the effect of biochar on all the key soil moisture properties and investigate the influence of different biochar characteristics.

Biochar physical and chemical properties vary due to the pyrolysis process conditions and type of feedstock used (Kloss et al., 2012). This changes the structure of the biochar and will invariably affect to what extent it can improve soil water retention. For example, Bouqbis et al. (2018) reported that woodchip biochar tends to have a higher water holding capacity when added to soils than a blend of paper sludge and wheat husk biochar. To understand how biochar affects soil water properties we must understand the specific characteristics of biochar that influence these changes. Understanding the mechanisms is important for reliable prediction of when and by how much biochar will improve soil water properties.

Thus, in this study, we performed a meta-analysis (MA) of published literature data to quantify the effect of biochar with different characteristics on soil water properties. A comprehensive quantitative MA of published data is vital to provide a clear picture of the properties of biochar that enhance its ability to improve soil moisture retention and to highlight areas where further research is needed. The utilization of MA in our article takes into consideration different studies involving a range of soil properties, biochar properties as well as management conditions. The results from this study are essential for informing biochar applications and for sound science-based policy making.

2. Materials and Methods

2.1. Data collection

An extensive literature search was performed using key words such as: biochar and soil physical properties and/or hydraulic properties, and/or water retention, and/or available water capacity, and/or moisture characteristics. The treatment and control were established as being identical for this MA with regards to all variables other than the addition of biochar. Therefore, only studies including a control (no biochar) and biochar treated soils were collected. Out of 150 published studies reviewed, 37 articles were selected that provided sufficient amount of reliable data on biochar-soil moisture effects (Table 1). Relevant data were retrieved from these studies regarding: soil texture, soil particle size distribution, rate of biochar application, feedstock, pyrolysis condition and biochar properties (particle size, specific surface area, porosity, skeletal density, bulk density, ash content, pH and elemental content). For cases where data were provided in graphical format, GetData graph digitizer (“GetData”, 2013), was used to extract relevant data points. These studies covered: 51 feedstocks, 16 pyrolysis temperatures, 20 particle size ranges, 12 soil textural classes and 45 rates of biochar application.

Studies without replicated treatments and control as defined were excluded from the MA. All studies that measured water content (field capacity (FC), available water content (AWC), permanent wilting point (PWP)) using either a Hyprop &WP4 device, pressure membrane meter or a tensiometer were included. Although these methods vary and have their own limitations (pressure plates and tensiometer data may not give accurate data at lower pressure (-1500kpa)) (Bittelli and Flury, 2009; Whalley et al., 2013), all these methods give information on the water tension and corresponding soil water content from which data for FC, AWC and PWP can be obtained. The data obtained from the 37 selected articles covered 94 datasets for FC, 107 datasets for AWC and 75 datasets for PWP. Where data for saturated hydraulic conductivity (K_{sat} 61 datasets), total porosity (TP 36 datasets) and bulk density (BD 131 datasets) were included, these were extracted as well (Table 1). All data extracted were mean values. Studies that measured water holding capacity (by drainage method) as FC were excluded because water holding capacity does not include water potential, which describes how freely water drains in soils and how much is available for plant use (O’Geen, 2013). Soil moisture content can be described across different potentials; 0 Mpa (saturation), -0.033 to -0.01Mpa (FC), -1.5 Mpa (PWP) and the difference between FC and PWP is known as the AWC (Kirkman, 2005).

2.2. Data grouping and treatment

The extracted analytical data were standardized to the same metric for each property (TP in %, FC, AWC and PWP in cm^3/cm^3, K_{sat} in cm/s, and BD in g/cm^3) to allow for comparison among different studies. Values of FC, AWC and PWP given in g/g were converted to cm^3/cm^3 by multiplying with the BD provided. The rate of biochar application was standardized to t/ha, where values were given in % weight, conversion was done using the BD and depth provided. In some instances, data required pre-grouping before the MA could be conducted, aiming for maximal in-group homogenisation. For experimental conditions, studies conducted in the laboratory, as pot trials and in green house were grouped as “Lab” conditions. Soil texture were grouped as sandy representing coarse textured soils (sandy loam, loamy sand and sand), loamy as medium textured soils (loam, silt loam, clay loam and silty clay loam) and clay as fine textured soils (clay and silty clay) texture classes based on the USDA soil classification system. Temperature was grouped based on the assumption that 500°C is the moderate pyrolysis temperature and produces more char (Winsley, 2007), with <500 and >500 °C representing low and high ranges, respectively. There are no specific range of data for classification of the other biochar parameters and therefore, they were grouped based on the range of data available. The rate of biochar application was grouped as <30 t/ha for low, 30 – 70 t/ha as medium, 71 – 200 t/ha as high and >200 t/ha as very high. Surface area was grouped as low (<20 m^2/g), medium (20 – 100 m^2/g), high (101 – 300 m^2/g) and very high (>300 m^2/g). Porosity was grouped as low (<50%), medium (50 – 70%) and high (>70%). While the biochar carbon content was grouped as low (<50%), medium (50 – 70%) and high (>70%). Experimental duration was considered during data collection but was not enough to include in the MA. A concise summary of the groupings and the studies that contributed to them are presented in Table 2.

2.3. Meta-Analysis (MA)

An MA was conducted to quantify the effects of biochar addition on soil water retention properties. MA allows for comparison of data from multiple studies (Borenstein et al., 2009). Standardization of the results was done by calculating the effect size following Borenstein et al. (2009). This allows for accurate statistical comparisons to be performed between results from multiple studies with differing experimental variables. The effect size was the natural logarithm of the response ratio (r) calculated as;

$$\ln r = \ln \frac{X_t}{X_c}$$

Where X_t = mean of biochar treated group and X_c = mean of control group for a given experiment. For each tested variable, $r > 1$ indicated an increase while $r < 1$ a decrease. The log transformed data were used in calculating overall effect and 95% confidence intervals for each group. For each parameter, groups with fewer than three treatments were excluded from the analysis. All data treatment and processing were done using Microsoft Excel 2010.

2.4. Forest plot presentation

Forest plots showing the effect size and 95% confidence interval for each group (represented by letters) were generated using Sigma plot 13.0. Each point represents the mean effect size and the size of the points represent the number of replicates from the combined studies in each group. The dotted lines represent the overall effect for each parameter. The group means were considered significantly different from each other if their 95% CI were not overlapping and significantly different from the control if not overlapping with zero.

3. Results

3.1. Influence of experimental setting (field/laboratory) and soil properties

The changes in AWC, K_{sat}, FC, PWP, TP and BD with biochar addition grouped by soil properties (experimental condition, soil texture, particle sizes and rate of biochar application) are shown in Fig 1.

For both field and lab experiments, biochar significantly increased AWC compared to the control due to an increase in FC. The increase was, however, more pronounced in lab experiments. When compared to field studies, AWC was on average 9.8% higher in lab studies. The same was true for FC where lab studies showed 3.4% increase in FC compared to field studies (Fig 1a&c). Biochar addition reduced K_{sat} in experiments conducted in the laboratory compared to the control, while in field studies, no significant difference was observed. It is pertinent to note that the number of datasets for field studies included in the MA (72) was much smaller than that of laboratory studies (226).

Biochar addition had the greatest effect in coarse textured soils (sand) with AWC, FC and PWP increasing by 32.9%, 23.9% and 22.2% compared to the control, respectively (Fig 1). The effect of biochar on fine textured soils (clay) was lower, but still showed a significant increase of AWC and FC by 9.1% and 3.5%, and a decrease of PWP by 0.4% compared to the control, respectively. A more detailed analysis showed that as the % sand in soil increased, the effect of biochar on the AWC, FC and PWP also increased, while the reverse was the case for % clay content. Biochar increased AWC by 37% in soils with >75% sand content. For >30% clay content, AWC was reduced by 31.2% (Fig 1).

On average, the addition of biochar reduced the soil K_{sat}. The greatest reduction in K_{sat} (64.6%) was found in coarse textured soils with sand content of more than 50%. Interestingly, biochar addition increased K_{sat} with increasing % silt and clay content in soil. There was a significant 28% and 36% increase in K_{sat} for fine textured and medium textured soils (loam), respectively. Generally, biochar increased the TP and reduced bulk density irrespective of the soil texture.

All application rates tested, i.e., <30, 30 – 70, 71 – 200 and >200 t/ha significantly increased AWC, FC, PWP and TP when compared to the controls with no biochar added. However, 30 – 70 t/ha showed no significant difference when compared to higher rates of application. There was also a significant reduction in K_{sat} with increasing biochar application rate. Compared to <30 t/ha, K_{sat} for 30 – 70 t/ha and 71 – 200 t/ha was significantly reduced by 54.8% and 68.1%, respectively. It is pertinent to note here that most studies used coarse textured soils (the number of K_{sat} datasets for coarse soils (39) was more than that of fine soils (18) and this may have influenced the result for K_{sat}. Addition of biochar to coarse textured soils reduces its K_{sat}, therefore, having more data from this soil type would lead to the result showing a reduction of K_{sat} on average. There was no significant difference between each of the rates of biochar application for TP and BD.

3.2. Influence of biochar production parameters

Figure 2 shows the effects of biochar addition to soil on AWC, K_{sat}, FC, PWP, TP and BD, grouped by biochar production parameters (feedstock type, temperature, heating rate and holding time).

The effect of the feedstock type on AWC, FC, PWP and TP was significant compared to the control, however, there was no significant difference among the various types of feedstock. Biochar produced from crop residue had no significant effect on K_{sat} and BD when compared to the control, while the woody biochar reduced K_{sat} and BD by 50% and 5.6%, respectively.

The effect of biochar on all assessed parameters were not dependent on the pyrolysis temperature. Sufficient data for heating rates were only available for FC and BD. The heating rate (in the range used) likewise did not change biochar's effect on any of the soil moisture parameters.

3.3. Influence of biochar physical properties

The changes in AWC, K_{sat}, FC, PWP, TP and BD with biochar addition grouped by biochar physical properties (particle size, specific surface area, skeletal density, bulk density and porosity) are shown in Fig 3.

Using biochar of different particle sizes grouped into <2 mm and >2 mm in this study did not significantly affect the changes observed for K_{sat}, PWP, TP and BD. In addition, biochar with a particle size of >2 mm had no significant effect on AWC and FC when compared to the control, however, smaller biochar particle size (<2 mm) increased AWC significantly by 38.2% when compared to >2 mm, most likely due to a 22.3% increase in FC.

Among the assessed biochar physical properties specific surface area (SSA) had the greatest effect on soil properties. Biochar with >300 m^2/g SSA increased AWC and FC by 70% and 52%, respectively, when compared to the control. The results also showed that as the SSA increased the effect of biochar on AWC also increased. Studies that used biochar with >300 m^2/g observed an increase in AWC by 33.3% when compared to those that used biochar with SSA of <20 m^2/g.

Insufficient data was available for assessment of the influence of biochars with a SSA >300 m^2/g on K_{sat}. For biochars with an SSA of 101 – 300 m^2/g (the highest group of SSA for K_{sat}) there was a 19.3% decrease in K_{sat} compared to the control, while for 20 – 100 m^2/g a 70% decrease was observed. The inconsistent pattern for K_{sat} values can be attributed to the varied soil textures used; for fine-textured soils, an increase in K_{sat} is beneficial, while for coarse-textured soils, a decrease is beneficial. For TP the changes that occurred as a result of varied biochar SSA were inconsistent and this is because the number of available studies were limited. The SSA of biochar were not related to the changes that occurred in the soil BD.

Biochar bulk density did not affect any of the soil water parameters assessed, however, an increase in skeletal density decreased the effect of biochar on AWC. This could be due to the increase in PWP as the skeletal density increased. Biochar skeletal density of >1 g/cm^3 decreased AWC by 20.5% and increased PWP by 27.4% when compared to < $1g/cm^3$. It is important to note that data for skeletal density were obtained from only 7 papers (39 datasets), and therefore further research on the impact of this biochar parameter is required to support a more comprehensive assessment of its relative impact on soil water characteristics.

Biochar effect on AWC increased with increase in its porosity. The effect of biochar on AWC increased by 42.1% and 61.2% when its porosity was >70% and 50 – 70% when compared to porosity of <50%. Also, biochar porosity below 50% did not cause any change in AWC as its ES was not significantly different from the control. Insufficient data were available for FC and PWP at <50% biochar porosity. No obvious change in FC were observed between 50 – 70% and > 70% biochar porosity. However, a porosity of >70% increased PWP by 16.9% when compared to 50 – 70%.

3.4. Influence of biochar elemental composition

Figure 4 shows the effects of biochar addition on AWC, K_{sat}, FC, PWP, TP and BD, grouped by biochar elemental composition (carbon, hydrogen, nitrogen and oxygen content, O:C and H:C). An increase in the carbon content of biochar caused an increase of its effect on AWC. Biochar with >70% carbon significantly increased AWC by 33.3% when compared to biochar with <50% carbon. A similar trend was seen in case of FC, where biochar with >70% carbon increased FC by 26%. Difference in biochar carbon content did not significantly affect the changes observed for K_{sat}, PWP and BD. Other elemental properties as well as the O:C and H:C did not have any effect on the changes that occurred in all the parameters.

3.5. Comparison between the effect of various biochar parameters on soil water properties of coarse and fine textured soils

Figures 5, S1, S2 & S3 show the different effects of biochar addition to soil on AWC, FC, K_{sat}, TP and BD for different soil textures broadly classified as coarse (soil texture grouped into sand) and fine textured soils (soil texture grouped into clay). Figures S1, S2 & S3 are included as supplementary information.

In general, the effect of biochar on AWC and FC was greater for coarse-textured soils (increase by 31.4 and 17.6%) than fine textured soils (increase by 13.6 and 6.1%). In fine-textured soil, the effect of biochar on AWC did not vary among various biochar properties except for the rate of application. AWC in treatments with <30 t/ha increased by 16.4% while there was no difference for treatments with 71-200 t/ha when compared to the control (Fig 5a). In coarse-textured soil biochar application rates of 30-70 t/ha increased AWC and FC by 23.5% and 36.78% compared to <30 t/ha application rate (Fig 5a and S1). Although no significant effect was observed between the various type of feedstocks on the AWC of both fine and coarse textured soils, for the coarse textured soil, all feedstock types increased AWC with woody feedstock having the greatest effect (33.3%). For fine textured soil, crop residue feedstock did not significantly change the AWC. The specific surface area of biochar did not affect the AWC and FC of fine-textured soils but it did affect coarse textured soils where AWC and FC increased with greater SSA. Assessment of the effect of biochar particle size showed that a small biochar particle size (<2mm) is essential to increase the AWC of coarse-textured soil (Fig 5a).

There was an obvious difference between the effect of biochar on K_{sat} of coarse and fine textured soils (Fig 5b). In general, biochar increased the K_{sat} of fine-textured soil by 39.3% and reduced that of coarse-textured soil by 61.8%. At application rate of <30 t/ha addition of biochar significantly increased the K_{sat} of fine-textured soil by 85% when compared to the control. In contrast, <30 t/ha biochar application had no effect on the K_{sat} of coarse-textured soil and there were significant differences between the various rate of application with decreasing K_{sat} as biochar rate increased. Woody feedstock increased K_{sat} by 24.8% and reduced it by 67.9% for fine and coarse textured soils, respectively, while crop residue biochar did not affect the K_{sat} in either soils. The increase in K_{sat} of fine-textured soil can be attributed to the increase in BD with biochar addition (Fig S3). Biochar generally increased the BD of fine-textured soil by 2.8% and decreased that of coarse-textured soil by 6.5% (Fig S3).

Biochar increased the TP for both soil types although the increment was greater in coarse-textured soils (7.9%) (Fig S2). The differences in pyrolysis temperature, biochar particle size and SSA did not influence how biochar affected K_{sat} TP and BD for both soil types. This could be due to lack of sufficient data for each soil type.

4. Discussions

4.1. Biochar improves soil structure and hence soil water properties

Biochar amendment generally improved the soil water properties (reduction in K_{sat} and increase in FC, AWC and PWP). This can be attributed to the modification of soil structural properties by biochar addition (Ajayi and Horn, 2016; Rasa et al., 2018). Using x-ray μ-tomography and SEM, biochar has been shown to increase total soil porosity, connectivity of pore space and number of pores (Quin et al., 2016; Zhou et al., 2019). This has a direct effect on soil water storage and mobility; increased number of pores (especially meso-pores) and total soil porosity lead to an increase in soil moisture retention.

The shape and size of the biochar particles also differ from soil particles and when incorporated into the soil can change the pore characteristics with direct effect on soil water properties. When fine biochar particles are added to coarse soil, the large pore spaces associated with coarse textured soils get filled up leading to reduced pore sizes and an increase in water retention. Beyond the pore spaces formed between the biochar particles and soil particles (interpores), the biochar intrapores (pores inside the biochar particles) also contribute to water retention (Hyväluoma et al., 2018b).

Water is generally stored and held in the biochar pores and an increase in biochar porosity will lead to an increase in water retention. However, the size of the pore determines whether the water will be available for plant uptake. The range of pore size distribution of biochar is very wide from nanometre to the micrometre ranges (Brewer et al., 2014). Pores in the micrometre ranges are the ones relevant for retaining plant available water (Kameyama et al., 2019). For soil related studies, pore sizes are classified in ranges of >75 µm (macropores), 30 – 75 µm (mesopores), 5 – 30 µm (micropores), 0.1 – 5 µm (ultra-micropores) and <0.1 µm (crypto pores) (SSSA, 1997). Macropores allow for movement of water, micropores retain water, but often so strongly that the water is not plant available. Water stored in the mesopores is retained and can be accessed by plant roots (Major et al., 2009). Therefore, a shift towards the meso and micro pore size ranges in biochar will lead to an increase in soil water retention especially for AWC.

An improvement in soil water properties after addition of biochar can also be attributed to an indirect effect due to increased soil aggregation (Herath et al., 2013; Pituello et al., 2018; Sun and Lu, 2014). In some studies a decrease in bulk density was observed, which can also be an indicator of increased soil aggregation (Burrell et al., 2016; Chen et al., 2010; Speratti et al., 2017). Soil aggregation refers to the arrangement and binding of soil particles to form secondary units (linked also to pore formation), which influence water movement. Addition of biochar to soil increases the formation of macroaggregates and aggregate stability (Ouyang et al., 2013; Wang et al., 2017), which improve both the hydraulic conductivity and water retention of soils.

4.2. Biochar's improvement of soil water properties depends on soil texture, application rate and its interaction

Greater effects of biochar on soil water properties were observed for laboratory studies compared to field studies (Fig 1). This can be explained by soil heterogeneity (Tammeorg et al., 2014) and lower control over factors, such as temperature and precipitation. Abel et al. (2013), studied the effect of maize biochar addition, both, in the field and laboratory and observed a 16.3% increase in AWC in the lab, but only an increase of 4.3% in the field. Field aging of biochar, resulting in changes to biochar properties, such as the specific surface area (Dong et al., 2017) or biochar hydrophobicity (Ojeda et al., 2015), can affect the response of biochar on soil water properties. Therefore, it is important to carry out systematic long-term field studies investigating the effect of biochar on soil water properties after a single-dose application.

The effect of biochar on soil water properties was significantly influenced by soil texture (Fig 1) with coarse textured soils showing the greatest response. The effect of biochar in AWC increased with the sand content of the soil and decreased with clay content. Coarse textured soils have large pores allowing for rapid movement of water and a reduced ability to retain water. With addition of biochar (especially biochar of finer particle size), these large pores are filled up leading to a reduction in water movement (K_{sat}) and consequently more water retention (AWC) (Figure 6). Fine textured soils inherently are composed of more micropores (storage pores) than coarse textured soils and therefore, the soil's AWC will respond less to biochar addition. This could also explain why at <30 t/ha, the effect of biochar on AWC was more pronounced in the fine textured soil than in the coarse textured soils (Fig 5). As coarse textured soils contain more macropores, much more biochar would be needed to fill up the pore spaces and increase its microporosity for an evident increase in AWC. This effect is maximised once the pores are filled, therefore, addition of more biochar (>70 t/ha) does not have any further effect as shown by our MA (Fig. 5). Studies that compared the effect of biochar in different soil textures reported a greater benefit in sandy soils relative to clayey soils (Ajayi and Horn, 2016; Kinney et al., 2012; Mollinedo et al., 2015).

An interesting result from this study is the increase in K_{sat} of fine-textured soils, while the K_{sat} of coarse-textured soils decreased (Fig 1). This likely explained by modifications of macroporosity and microporsity of the different soil textures (Fig S2). Soil hydraulic conductivity is controlled by pore size, geometry and distribution and not only by the total soil porosity. Coarse textured soils have a higher K_{sat} than fine-textured soils even though their total porosity is lower (Schoonover and Crim, 2015). This is because coarse soils have large pore sizes; large and continuous pores have greater hydraulic conductivity (Karahan and Ersahin, 2016). Addition of biochar to coarse-textured soil lead to a shift from macro-pores (transmission pores) to meso/micro-pores (storage pores) reducing its K_{sat} and increasing moisture retention. In fine-textured soils (especially if compacted due to poor management), biochar addition leads to a shift from ultramicro-pores to micro and macro-pores, and an increased formation of macro aggregates effectively opening up the soil structure and increasing its K_{sat} (Amer et al., 2009; David, 2003; Zaffer and Sheng-Gao, 2015). Although biochar had relatively little effect on the AWC of fine-textured soils in our MA, it was able to increase its K_{sat}, which is very important for water penetration. Soils with very high clay content are easily prone to compaction due to poor management, which can restrict movement of water in the soil and thus increase the risk of runoff. An increase in K_{sat} with biochar addition can help mitigate these problems.

The observed changes in soil water properties were also related to biochar application rates. A linear increase in AWC with application rate and reduction in K_{sat} have been reported in many studies even with high application rates of about 400 t/ha (Bruun et al., 2014; de Melo Carvalho et al., 2014; Lim et al., 2016). In contrast, Obia et al. (2016) reported no significant changes in water retention properties with the application of rice husk biochar even at 10% dry weight basis (20 t/ha) on a heavy clay soil. Villagra-Mendoza and Horn (2018) observed significant difference in AWC only between the control and 5% application rate for a sandy loam using mango tree biochar, while 2.5% did not significantly change the AWC. This inconsistency suggests that application rate of biochar for soil water improvement may depend on the biochar and soil type. Importantly our results demonstrate that in coarse textured soils biochar needs to be applied at >30 t/ha to affect soil water properties, while in fine textured soils application rate of <30 t/ha is sufficient and could be even more beneficial than the application of 30-70 t/ha (Figs 5a & b).

Depending on feedstock used, the price of biochar could range from US$ -222 to 584/t (Shackley et al., 2011). Biochar application rate above 70 t/ha may not be economical in regard to effect on water relations in soil. Even using an application rate of 30 t/ha could amount to US$17,520/ha. It is therefore imperative to determine the optimum biochar application rate for each biochar and soil type and how to modify biochar to increase low-dose-high efficiency benefit.

4.3. Feedstock and pyrolysis temperature alone are weak predictors of biochar's effects

The performance of biochar as a soil amendment is governed by its properties which can vary largely depending on biomass feedstock and pyrolysis conditions (Kloss et al., 2012; Zhang et al., 2017). E.g. Zhao et al., 2013 reported that feedstock had more influence on pore volume and cation exchange capacity than pyrolysis temperature, while the latter had a greater influence on surface area and pH.

Our MA showed that biochar from woody feedstock, but not from crop residues, decreased K_{sat} significantly and increased FC (Fig 2). This can be attributed to a significant reduction of BD by woody biochar (Fig 2). The more pronounced effect of biochar made from woody residue on K_{sat} compared to biochar from crop residues could be a result of its greater surface area and porosity increasing its ability to control soil water functions (Wang et al., 2013). The porosity of biochar made from woody feedstock has been found to be greater than that of crop residue (Punnoose and Anitha, 2015). This is due to the differences in the biomass cell structure, shape, size and composition. Kinney et al. (2012) reported a higher FC for a sandy soil using an apple wood biochar over a magnolia leaf biochar both pyrolyzed at 400°C at 3 different rates of 2, 3 and 7% by weight. Other individual studies (Burrell et al., 2016) and a MA study by Omondi et al. (2016) reported a significant increase in AWC using a crop residue biochar over a woody biochar. In our MA, we could not confirm this result. These inconsistencies point to the fact that feedstock alone may not be enough to determine the efficacy of biochar for improving soil water properties. Even amongst similar feedstock, varying biochar effect can be obtained (Suliman et al., 2017).

None of the pyrolysis conditions including temperature influenced the effect of biochar on all the investigated soil properties (Fig 2). This could be due to the grouping of pyrolysis temperature into 2 which was based on the available literature. In other studies, however, AWC, FC and K_{sat} were greatest when biochar produced at a higher temperature (>500°C) was used (Kinney et al., 2012; Omondi et al., 2016). The increase in soil water retention properties by addition of biochar produced at high temperature (600 -700°C) over that produced at low temperature (300 - 400°C) in other studies was attributed to the increase in biochar porosity as pyrolysis temperature increased (Jeffery et al., 2015; Lei and Zhang, 2013). While, many studies show that higher pyrolysis temperature increase the overall pore space of biochar, the pore size relevant for plant available water storage does not seem to increase (Gray et al., 2015; Hyväluoma et al., 2018a; Hyväluoma et al., 2018b). This clearly demonstrates that pyrolysis temperature is of less importance for soil water retention as confirmed by our MA.

In addition, there is no straightforward link between pyrolysis temperature and biochar properties. Using the same pyrolysis temperature for different feedstocks, woody feedstock produces biochar with a much higher porosity and SSA compared to some agricultural residues and food waste (Lei and Zhang, 2013). The SSA, pore volume and pore size of a biochar produced from sewage sludge was shown to increase proportionally from 14.28 to 67.6 m^2/g, 0.06 to 0.10 cm^3/g and 2.7 to 3.8 nm, respectively, with an increase in temperature from 500 - 900°C (Lu et al., 1995; Chen et al., 2014; Yuan et al., 2013). In contrast, Jin et al. (2016) reported a reduction in SSA from 8.45 – 5.99 m^2/g as pyrolysis temperature increased from 550 - 600°C for a sewage sludge biochar. Chen et al. (2014) used a holding time of 20 minutes and a constant flow of N_2 at 0.03 L/min, while Jin et al. (2016) used a holding time of 1 hour and a constant flow of N_2 at 1 L/min. This shows that pyrolysis temperature alone is not sufficient to determine the biochar properties, heating rate and holding time are also important.

A simple increase in pyrolysis temperature is unlikely going to increase the ability of biochar to improve soil water retention since it does not increase the pore volume relevant to retain plant available water, this can rather be inferred from specific biochar characteristics (pore volume, particularly mesopores, and specific surface area). Though pyrolysis temperature can have an indirect effect through affecting biochar hydrophobicity and hence, the water uptake of biochar (Das and Sarmah, 2015; Gray et al., 2014).

4.4. Specific biochar characteristics are key to predict the effect on soil-water relations

During pyrolysis, the feedstock undergoes chemical reactions, including decomposition, polymerization and fragmentation, which change its structural and elemental properties (Moldoveanu, 2019). Characterizing and understanding the properties of biochar is very important to enable its site-specific usage and to determine optimum rate of application.

Based on the results of this MA, it is clear that biochar physical properties, in particular, SSA, are the key factors affecting soil water properties (Fig 3). Higher biochar SSA increases the adsorption capacity of the biochar leading to increased water retention (Freeman et al., 1995). Many individual studies have observed an increase in water retention with increasing biochar SSA (Ajayi and Horn, 2016; Liu et al., 2017; Speratti et al., 2017; Suliman et al., 2017; Villagra-Mendoza and Horn, 2018). In addition, biochar's surface chemistry and hydrophobicity are also important factors. The presence of acidic and oxygenated functional groups on the biochar surface can enhance its water holding capacity by changing its hydrophobicity. Adding hydrophobic biochar to soil can make the whole system hydrophobic leading to a reduction in water retention. Studies have shown that biochars produced at lower pyrolysis temperatures are typically hydrophobic due to aliphatic surface groups (Das and Sarmah, 2015; Gray et al., 2014). Pyrolysis temperatures of >400°C are typically needed to produce hydrophilic biochar, hence maximising water uptake (Das and Sarmah, 2015)."

The MA results also show that the effect of biochar on AWC increases with a decrease in biochar particle size and its skeletal density (Fig 3). Biochar particle size determines soil pore volume, pore sizes and shapes and thus would influence soil water movement and storage (Gray et al., 2014). Finer particle size biochar would fill in the large pore spaces in a coarse-textured soil shifting the inter-particle pore size distribution to the meso and micro pore ranges, leading to an increase in water retention in the new, smaller pore spaces. Previous studies have reported an increase in AWC when smaller biochar particle sizes (<0.5 mm) were used compared to larger ones (>1 mm) (Eibisch et al., 2015; Morgan, 2014). In contrast, Liu et al. (2017) and Obia et al. (2016) reported a decrease in AWC with decreasing biochar particle size (with <0.25 as the smallest size) and attributed this to a reduction in biochar internal porosity with grinding. This could mean that just considering the size of the biochar particle is not enough, but the grinding method used in reducing the particle size and the resulting density is also important.

The density of biochar controls both its interaction with soil hydrologic processes and its movement in water. An increase in skeletal density may result in a reduction in biochar intra-porosity which could lead to less soil water being retained (Liu et al., 2017).

Apart from the carbon content, no biochar elemental properties influenced soil water characteristics (Fig 4). Biochar carbon content would have an indirect effect on soil water properties. Adding biochar with high carbon content will increase soil organic matter bonding, improving soil aggregation (Juriga and Šimanský, 2018). These would contribute to the creation and stability of soil aggregates and pores, and invariably lead to increased soil water retention (Rawls et al., 2003). In addition, in most cases a lower biochar carbon content means that the biochar has a higher mineral content, which does not contribute to biochar's porosity. A lower proportion of carbon means less intrapore space for soil water retention compared to a comparable biochar produced under the same conditions. Although, all other biochar elemental properties did not influence its effect on soil water retention, some structures on the biochar surface can increase its hydrophobicity and therefore, reduce its ability to absorb and retain water despite its high porosity (Gray et al., 2014; Jeffery et al., 2015). Therefore, some pre- and post-pyrolysis treatment may be needed to reduce biochar hydrophobicity and increase its efficacy for improving soil water retention.

5. Future research challenges

- The number of studies conducted in the field is small compared to the laboratory and green house studies. Our MA showed that there is a discrepancy between the results in the field and those conducted in the laboratory. This is likely due to the differences in soil properties, weather and environmental conditions in the field. It is therefore pertinent to conduct more field trials to investigate how biochar affects soil water properties under varying environmental conditions.

- Biochar undergoes aging which changes its properties. This can influence the effect of biochar on soil water properties over time. Most of the studies used in the MA were conducted for less than 2 years. Therefore, it is important to carry out systematic long-term field studies investigating the effect of biochar on soil water properties after a single-dose application and the related changes in biochar properties.
- Insufficient data was available for biochar surface functionality and hydrophobicity to be included in the MA. These two properties are also very important in controlling the ability of biochar to enhance soil water retention. More research in this area is necessary.
- Most of the studies used >30 t/ha biochar application rates. Considering the costs of biochar, this will unlikely result in a return on the investment. It is, therefore, crucial to conduct more research on the modification of biochar (using pre- or post-pyrolysis treatments) to increase low dose – high efficiency benefit.

Conclusion

This comprehensive MA of the available literature assessed for the first time the current state of knowledge on the effect of different biochar properties on the full set of key soil hydraulic parameters. The results showed that application of biochar significantly increases AWC and reduces saturated hydraulic conductivity for coarse textured soils, while increasing saturated hydraulic conductivity of fine textured soils. The increase in AWC was directly associated with increase in FC and PWP and indirectly with reduction in BD (which signifies an improvement in soil structure). The effects of biochar, however, varied with soil conditions, pyrolysis conditions and biochar characteristics. The greatest effect of biochar on soil water properties was observed for coarse-textured soil for studies conducted in laboratories with application rates of 30 – 70 t/ha. The application rate needed for improvement of soil water properties was lower in fine textured soils (<30 t/ha) compared to coarse textured soils (>30 t/ha). Biochar had a greater effect on water retention in soils with higher sand content. The results also showed that neither feedstock nor pyrolysis temperature alone are sufficient to predict the performance of biochar in different soils. Biochar physical characteristics such as particle size, SSA and porosity were the key factors. Furthermore, both inter-particle pore space and intra-particle pore space play a very important role in biochar-soil water relations.

Future research needs to focus on long-term field trials, effect of biochar ageing on soil water retention, optimum application rate of biochar in different soils and the relationship between surface functionality and biochar performance. Such understanding would enable development of low-dose-high efficiency applications. Such applications, where relatively small amounts of biochar generate a large effect on soil water retention, are the most likely to be adopted in practice. This MA signposts the directions for future research on these critical aspects.

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Table 1: Literature Database

	Experimental parameters													Target parameters					
Author & Year	**Feedstock**	**Pyrolysis Temperature**	**Particle Size**	**Surface Area**	**Skeletal Density**	**Bulk Density**	**Porosity**	**Biochar Ash content**	**Biochar C content**	**Biochar H content**	**Biochar N content**	**Biochar O content**	**Soil Texture**	**Total Porosity**	**Field Capacity**	**Available Water Content**	**Permanent Wilting Point**	**Saturated hydraulic conductivity**	**Bulk Density**
Abel et al., 2013	X	X			X	X	X		X				loamy sand	X			X		X
Ajayi and horn, 2017	X	X		X	X				X				sandy loam, fine sand & silty clay loam	X		X			X
Amoakwah et al., 2017	X	X	X						X	X			Sand	X		X			X
Barnes et al., 2014	X	X				X		X	X		X		sandy loam & clay loam		X			X	X
Baronti et al., 2014	X	X	X	X		X			X	X	X		sandy clay loam			X			X
Basso et al., 2013	X	X						X	X	X	X	X	sandy loam	X	X	X	X		X
Bayabil et al., 2015	X	X	X					X	X				Sand		X	X	X		
Burrell et al., 2016	X	X		X				X	X				sandy loam & clay loam		X	X	X		X
Chen et al., 2010	X	X		X		X			X	X	X		Clay			X			X
de Melo carvalho et al., 2014	X	X	X	X		X							sandy loam			X			
Duarte et al., 2019	X	X	X	X					X				Fine sand & clay loam			X			
Eibisch et al., 2015	X	X	X	X					X				loamy sand	X					X
Hardie et al., 2014	X	X			X	X	X						sandy loam	X	X	X	X		X
Herath et al., 2013	X	X						X	X	X	X	X	silt loam		X			X	

Jeffery et al., 2015	X	X					X	X	X				Sand			X		X	
Jin et al., 2019	X	X	X										Clay loam		X	X	X	X	X
Kameyama et al., 2014	X	X	X	X	X				X	X	X	X	Clay	X					
Karer et al., 2013	X	X	X						X	X		X	Silt loam & clay loam		X	X	X		X
Kinneya et al., 2012	X	X							X	X	X		Sand & clay		X				
Kiode et al., 2015	X	X											sandy loam, silty clay loam & loam						X
Li et al., 2018	X	X	X	X			X		X	X	X	X	silt loam & silty clay					X	X
Lim et al., 2016	X	X	X			X		X	X	X	X	X	fine sand, loam & clay					X	X
Liu et al., 2017	X	X	X		X			X	X	X	X		Sand	X	X	X	X		X
Ma et al., 2016	X	X							X				clay loam		X	X	X		X
Martinsen et al., 2014	X	X		X	X				X	X			Sand, loam sand & sandy loam		X	X	X		X
Mollinedo et al., 2015	X	X	X	X				X	X	X	X	X	sandy loam & clay loam		X	X	X		
Morgan, 2014	X	X	X										sandy loam		X	X	X		X
Obia et al., 2018	X	X	X						X	X	X		Clay		X	X	X		
Obia et al., 2016	X	X	X	X		X			X	X	X		sandy loam	X	X	X	X		X
Ojeda et al., 2015	X	X							X	X	X	X	sandy loam			X	X		X
Ourendnicek et al., 2018	X	X	X	X				X	X	X	X	X	sandy loam & loam					X	X
Quin et al., 2014	X	X	X	X			X		X				Sand		X	X	X		X
Ouyang et al., 2013	X	X	X	X	X				X	X		X	Silty clay & sandy loam			X		X	
Speratti et al., 2017	X	X	X	X	X				X				Sand			X			X
Suliman et al., 2017	X	X		X	X	X	X		X				Sand & loamy sand		X	X	X		
Tammeorg et al., 2014	X	X			X				X	X			Loamy sand	X	X	X	X		X
Wang et al., 2019	X	X	X	X					X	X	X	X	Silt loam & fine sand		X	X	X		

Table 2: Matrix showing variables, groups and number of datasets from the combined studies included in each group

Soil properties			Pyrolysis condition			Biochar physical properties			Biochar Elemental properties		
Variables	**Group**	**No. of datasets**	**Variables**	**Group**	**No. of datasets**	**Variables**	**Group**	**No. of datasets**	**Variables**	**Group**	**No. of datasets**
Experimental condition	Field	72	Feedstock	Woody	133	Biochar Particle size	<2 mm	130	Carbon	<50%	23
	Lab	226		crop residue	152		≥2 mm	14		50 -70%	96
Soil texture	Sandy	216		animal manure	13	Specific surface area	<20 m^2/g	41		>70%	121
	Loam	49	Temperature	≤500 °C	152		20 – 100 m^2/g	11	Nitrogen	<0.5%	49
	Clay	33		>500 °C	146		101 – 300 m^2/g	54		0.5 – 1%	40
% sand	<50%	18	Heating rate	<10 °C/min	21		>300 m^2/g	24		>1%	40
	50 – 75%	27		>10 °C/min	19	porosity	<50%	6	Oxygen	<10%	48
	>75%	26	Holding time	<20 sec	47		50 - 70%	19		10 – 20%	10
% silt	<20%	32		20 – 120 sec	60		>70%	39		>20%	33
	20 – 50%	30		>120 sec	100	Skeletal density	<1 g/cm^3	39	Hydrogen	<3%	22
	>50%	10					≥1 g/cm^3	34		>3%	28
% clay	<15%	38				Bulk density	<0.3 g/cm^3	47	O:C	<0.1	23
	15 – 30%	24					≥0.3 g/cm^3	25		0.1 – 0.2	19
	>30%	10								>0.2	17
Rate of application	<30 t/ha	77							H:C	<0.5	45
	30 – 70 t/ha	102								0.5 – 1	19
	71 – 200 t/ha	105								>1	11
	>200 t/ha	9									

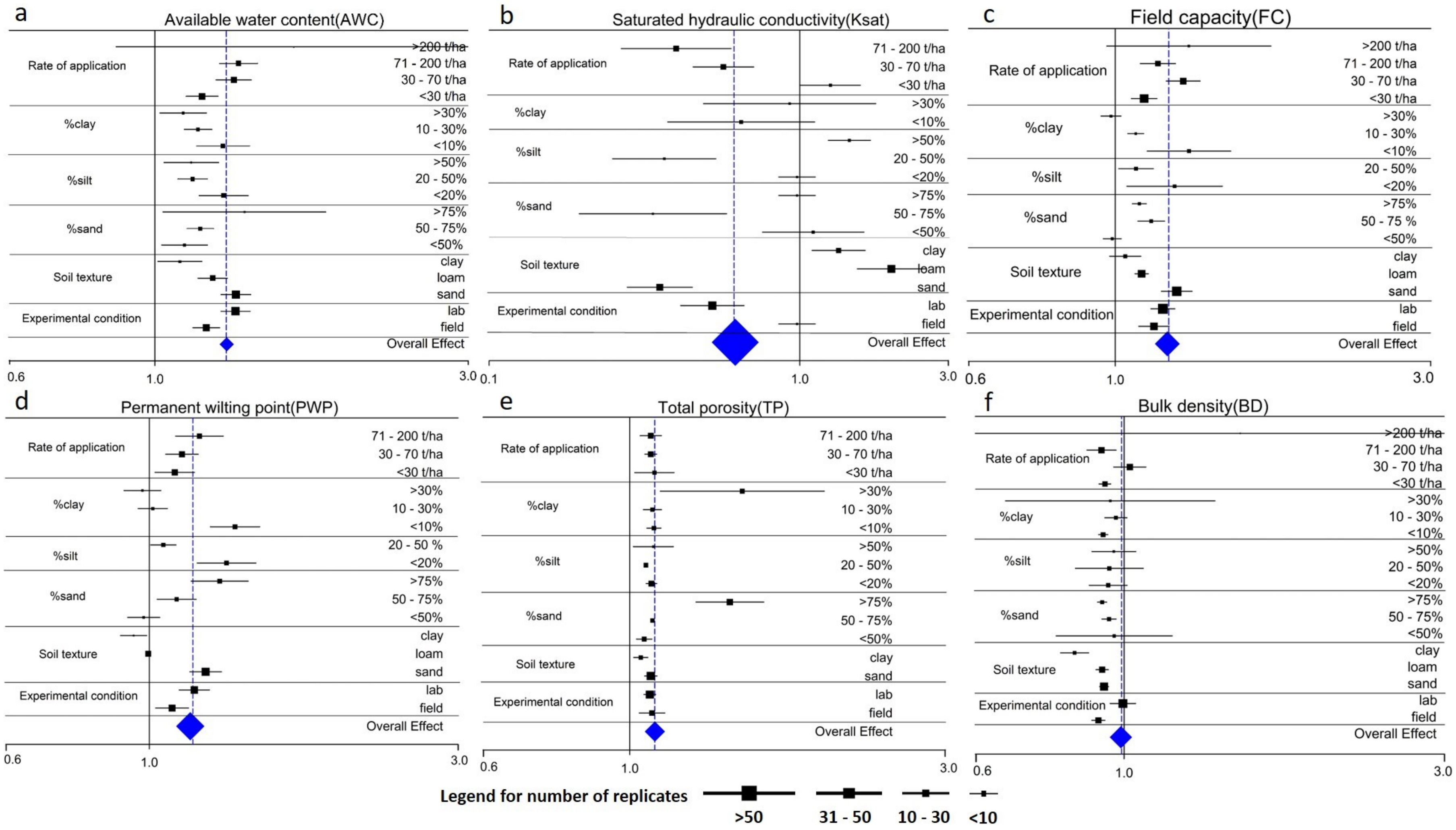

Figure 1: A forest plot showing the mean changes in AWC, Ksat, FC, PWP, TP and BD due to biochar addition to soil for different categories grouped by soil conditions. Points show treatment effect for a given group, size of point show the total number of replicates (n) from the combined studies, bars show 95% confidence interval while blue tick line show overall effect (grand mean)

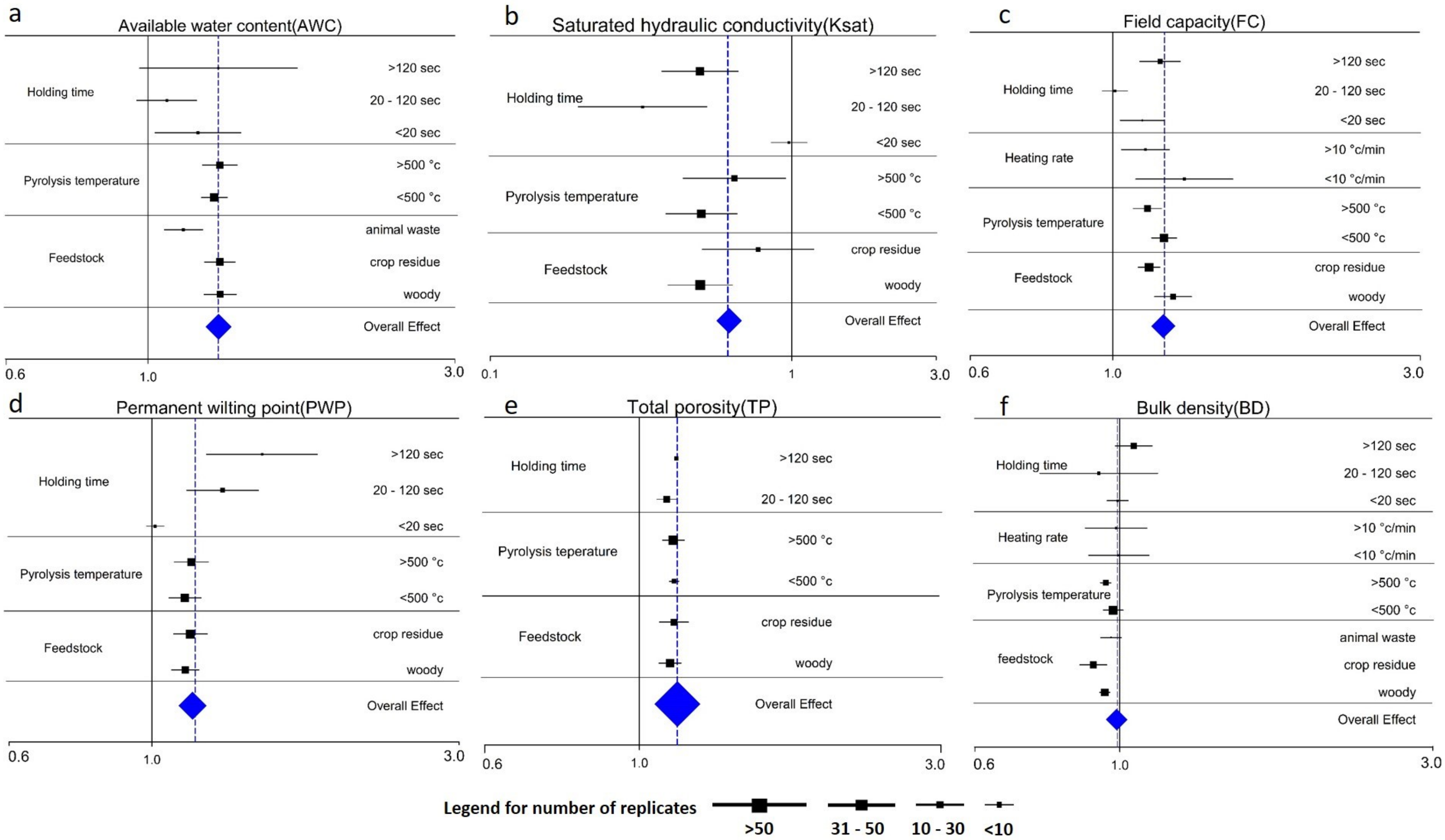

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Figure 2: A forest plot showing the mean changes in AWC, Ksat, FC, PWP, TP and BD due to biochar addition to soil for different categories grouped by pyrolysis condition. Points show treatment effect for a given group, size of point show the total number of replicates (n) from the combined studies, bars show 95% confidence interval while blue tick line show overall effect (grand mean)

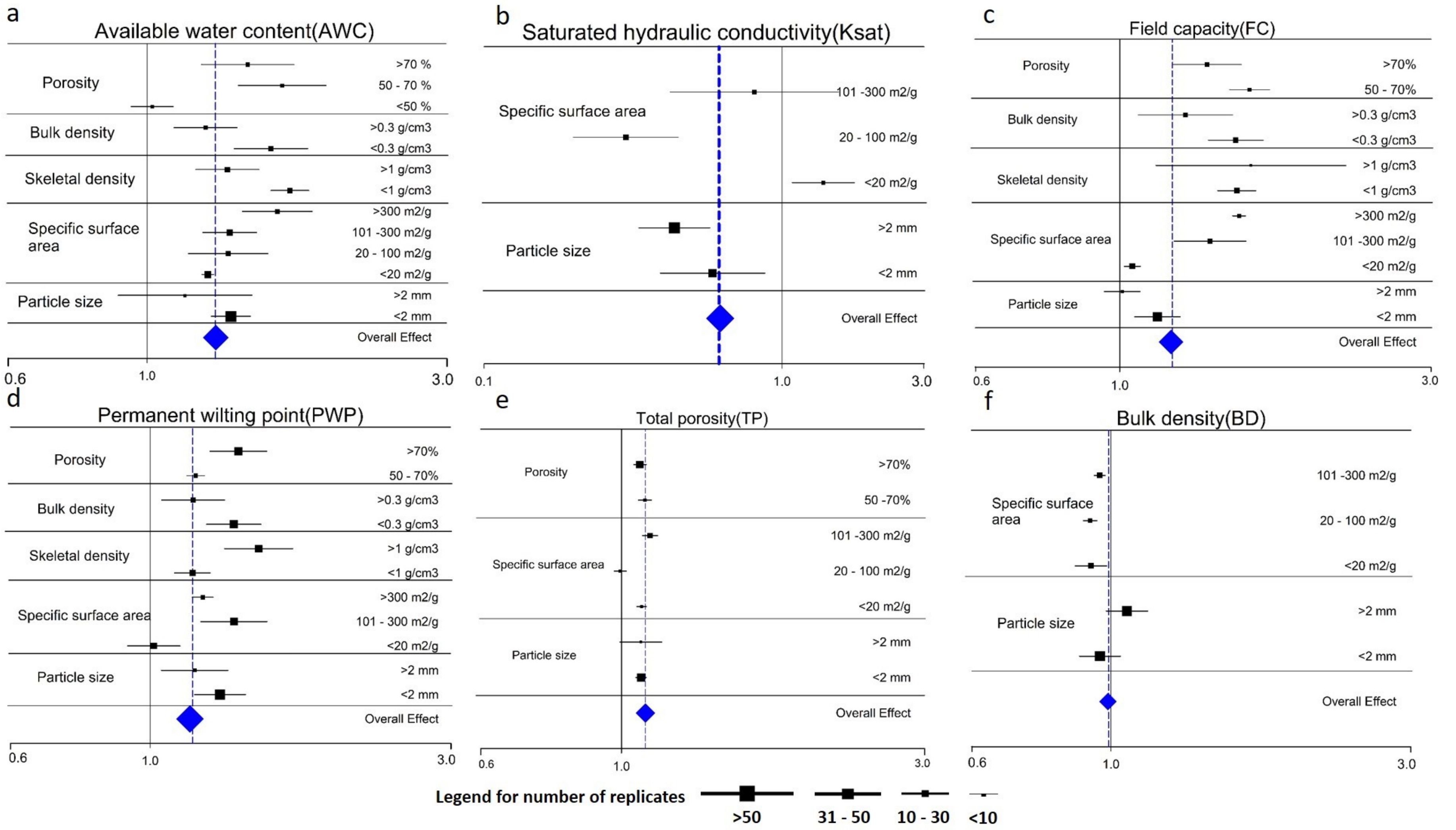

Figure 3: A forest plot showing the mean changes in AWC, Ksat, FC, PWP, TP and BD due to biochar addition to soil for different categories grouped by biochar physical properties. Points show treatment effect for a given group, size of point show the total number of replicates (n) from the combined studies, bars show 95% confidence interval while blue tick lines show overall effect (grand mean)

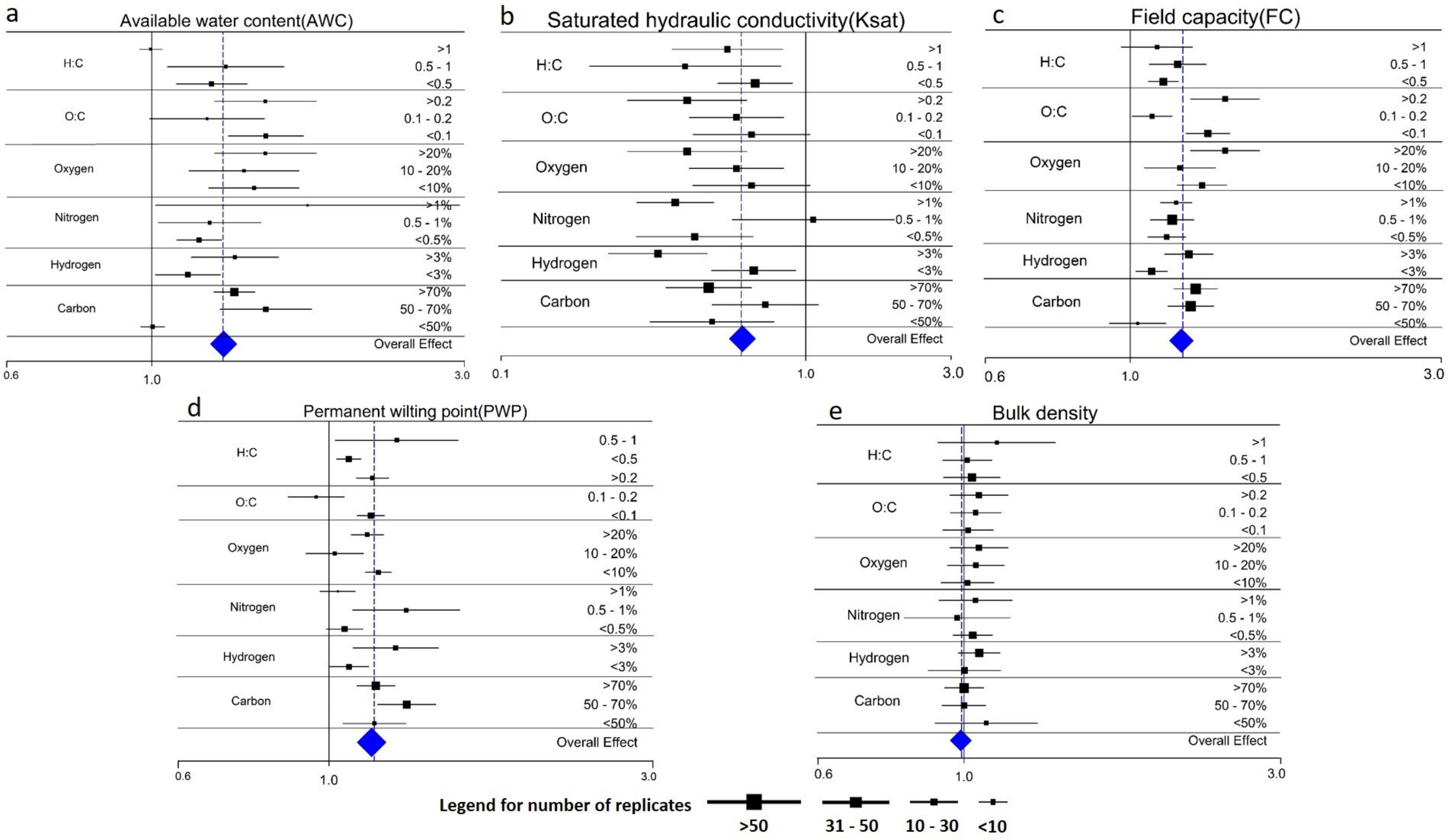

Figure 4: A forest plot showing the mean changes in AWC, Ksat, FC, PWP, TP and BD due to biochar addition to soil for different categories grouped by biochar elemental properties. Points show treatment effect for a given group, size of point show the total number of replicates (n) from the combined studies, bars show 95% confidence interval while blue tick lines show overall effect (grand mean)

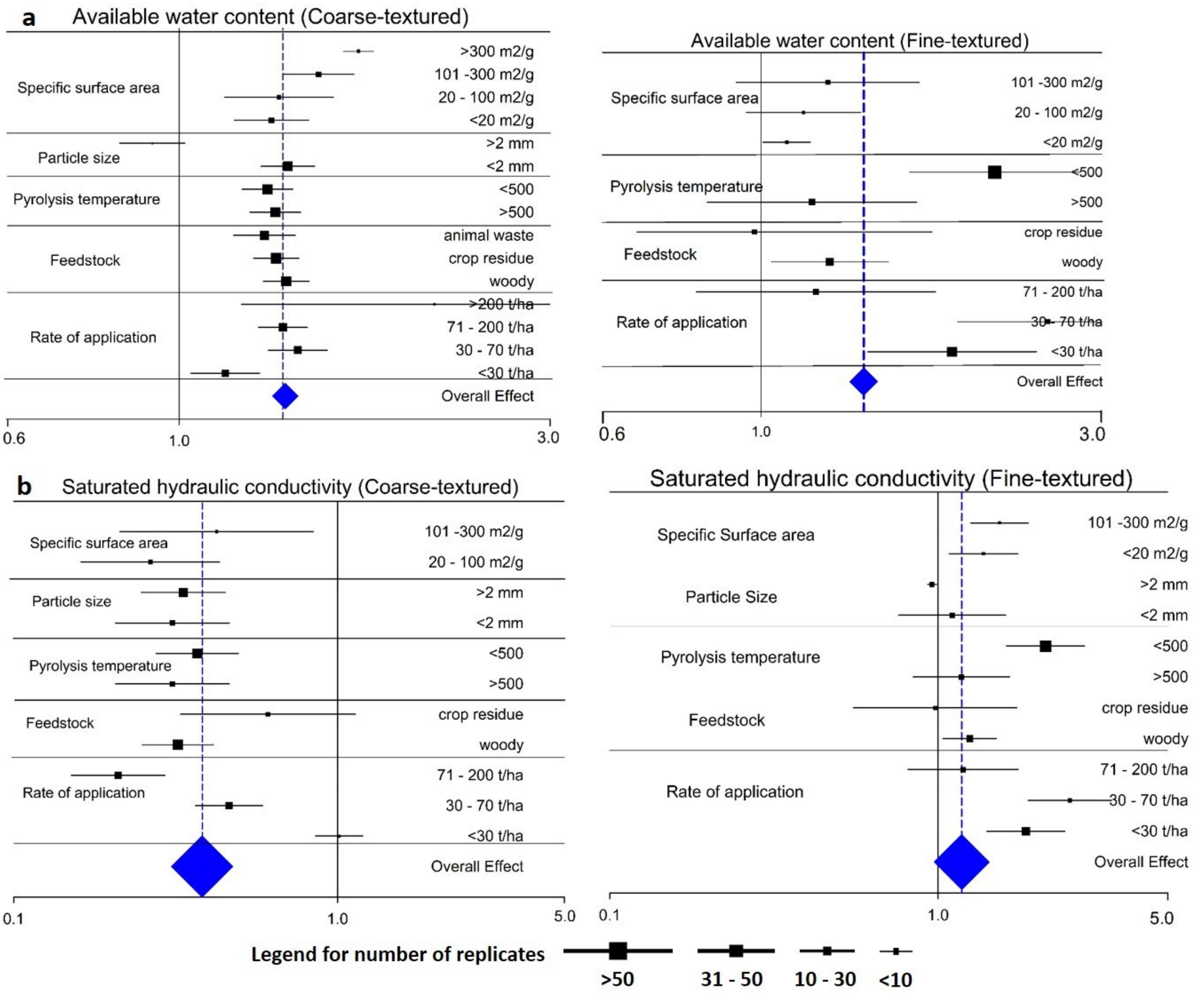

Figure 5: A forest plot showing the mean changes of available water content due to biochar addition to soil of different textures. Points show treatment effect for a given group, size of point show the total number of replicates (n) from the combined studies, bars show 95% confidence interval while blue tick line show overall effect (grand mean)

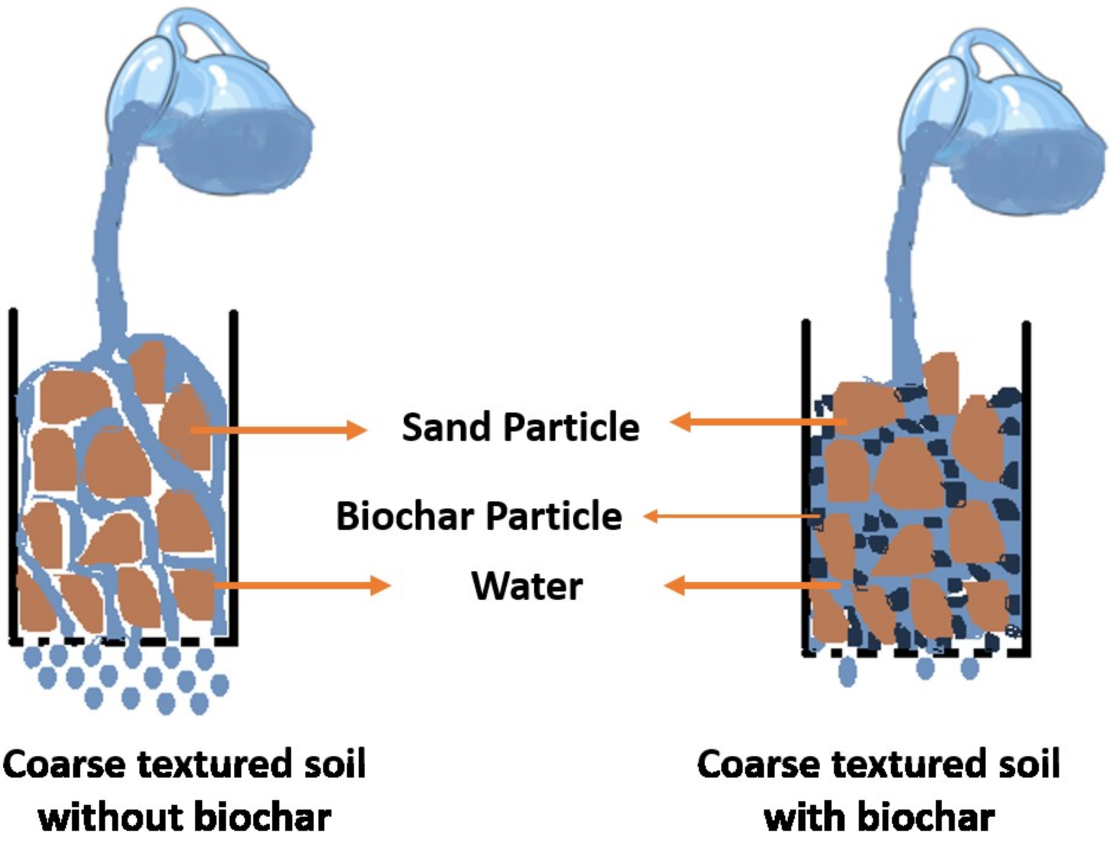

Figure 6: Schematic diagram illustrating the effect of biochar on K_{sat} of coarse textured soils

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