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Soil Use and Management – Revised Version 2

How good is the evidence that soil applied biochar improves water holding capacity?

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Abstract

Biochar application to soil is suggested as a way of enhancing soil fertility by increasing the availability of nutrients and water. The former is perhaps better documented while the latter has less experimental support. This review critically investigates recent literature which focuses on determining if biochar induces increases in plant available water and that this provides part of the explanation for possible increases in crop yield. A number of studies suggests that biochar increases crop yields and this is linked to enhancement of soil water content and increased crop growth. However, many of these studies fail to fully consider if the measured biochar increases of 10-30% in soil water content, were actually responsible for an increase in plant available water for crop growth. There is also limited evidence of increased crop yields when biochar is used in field experiments. While biochar soil application may increase soil water content, this appears to most likely occur with free draining coarsely textured sandy soils. As yet there is limited evidence that biochar improves soil water content in temperate soils and even less that it facilitates plant tolerance to drought stress. More recent literature shows the use of methods which quantify soil biochar changes with respect to plant water availability. However, despite some advances in our understanding of biochar's mode of action, there are still only a few studies which link increases in plant available water with increased crop yields, and particularly with respect to the longer-term use and functionality of soil applied biochar.

Keywords*:* Biochar, drought**,** agricultural productivity, plant available water, matric potentials, soil water

Relevance of soil applied biochar and the aims of this review

The importance of biochar as a recalcitrant source of carbon in soils and its possible carbon sequestration benefits (The Royal Society 2009a) are put to one side, despite the limited number of quantitative studies describing its long-term behaviour in terrestrial ecosystems (Forbes *et al.,* 2006; Jeffery *et al.,* 2011), this still remains an important issue (Zhang *et al*., 2016). Here the focus is on biochar's ability to increase agricultural yields via increases in soil water content (SWC) (Lehmann *et al.,* 2006; Atkinson *et al*., 2010; Woolf *et al.,* 2010; Omondi *et al.,* 2016). There is considerable interest in understanding how soil applied biochar might increase crop yields, particularly if this occurs by reducing drought stress (Blanco-Canqui 2017). Much attention is now rightly given to the importance of 'soil health' and its link with agricultural yields, as the challenge to produce more food globally continues to increase (The Royal Society 2009b). This can only be achieved through global adoption of sustainable practices and a reversal of global soil degradation.

Evidence, initially from South America (Amazonian, 'dark earths' soils or *terra preta*), where anthropogenic soil biochar incorporation has occurred, often over 1000s of years (Kern *et al.,* 2003; Lehmann and Rondon 2005), supports the notion of increased crop yields, as does more recent experimental evidence from soils in tropical regions (Lehmann *et al.,* 2003b; Steiner *et al.,* 2007; Blackwell *et al.,* 2009; Jien and Wang 2013). This is perhaps, not unexpected given the climatically induced high rates of soil organic carbon turnover, poor soil physical structure (a sandy texture), high rates of mineralisation, and low cation exchange capacity, apparent in acidic tropical soils (e.g. ultisol, oxisols and arenosols). This has led to a decline in soil organic matter (SOM) and the leaching of soils, which become minerally deficient (Liang *et al.,* 2006; Steiner *et al.,* 2007; Richter and Babbar 1991). It is, however, important to note that the constituents of these *terra preta* soils are far more complex than just sites of high charcoal/biochar addition (Kampf *et al*., 2003; Lehmann *et al*. 2003b). Their analysis shows a number of constituent candidates, not just SOM, as potential crop resources which might enhance agricultural yields relative to untreated soil (Glaser *et al.,* 2001, 2002; Lehmann *et al.,* 2003ab; DeLuca *et al.,* 2009; Steiner 2007; 2008; Zong *et al.,* 2016). It is, however, not clear given the differences in climate, soil type and function, how extensive the yield increases seen in *terra preta* soils translate into increases in yields in other regions, where soils and climates are different from the tropics (Liu *et al.,* 2013; Jeffery *et al.,* 2017). Some experiments suggests that the absence of detectable increases in crop yields when biochar is used in northern temperate regions, can be explained primarily through differences in soil type and the use of soils experimentally (Table 1), which are not nutritionally deficient or physically poor as is the case with many tropical soils (Atkinson *et al*., 2010; Jay *et al.,* 2013; Jeffery *et al.,* 2017). What is much less clear are the possible effects that biochar might have beyond the more obvious soil and crop nutritional increases, particularly those linked to increased SWC and tolerance to crop drought stress (Pressler *et al*., 2017). Drought tolerance may in part be responsible for Amazonian *terra preta* increases in crop yields and provide a mechanism to explain agricultural yield increases outside tropical climates (Atkinson *et al.,* 2010).

The aim of this work is to examine published claims which suggest that the application of biochar enhances crop available water and that this provides a mechanism by which yields increases. The evidence has been reviewed critically to determine if biochar application increases not only SWC, but is also accompanied by a measured increases in water available to the crop. As soils contains more water than can be abstracted and used for plant growth, the primary interest here is to determine if changes in SWC translate into more water available for crop growth, i.e. increased 'plant available water' (PAW). While understanding that the effects of increases in SWC, due to biochar application, are potentially different from those of increased PAW.

Suggestions that biochar may increase PAW are discussed based on the initial observations derived from *terra preta* soils in Amazonia and consideration is given to whether these translate into benefits outside these tropical regions and climates. Despite repeated suggestions, within a number of biochar reviews, clear evidence for biochar enhanced PAW is hard to find, with the predominant exception of measurements linked to coarse and/or sandy soils (Uzoma *et al*., 2011; Novak *et al*., 2012; Abel *et al.,* 2013; Basso *et al.,* 2013; Mulcahy *et al*., 2013; Saarnio *et al*., 2013; Bruun *et al*., 2014; de Melo Carvalho *et al*., 2014; Laghari *et al*., 2015; Obia *et al.,* 2016; Glab *et al*., 2016; Omondi *et al*., 2016; Blanco-Canqui 2017) .

Why might soil biochar application increase crop yields?

Water within the soil is a particularly important aspect of crop production. Too little, or too much water and crops will not achieve their expected yields and aspects of crop quality can be effected both negatively and positively. Soil water content (θ) can be expressed gravimetrically (θ_g; g water g^{-1} soil), or volumetrically (θ_v; cm^3 water cm^{-3} soil) and it is influenced by gravity, the forces of capillarity (pressure), adsorption (electrostatic) and osmosis (solute). While it is the forces of capillarity and adsorption, in particular, that impact on plant available water (θ_{paw}). Plant available water (PAW) being determined by the difference between the water held at field capacity (θ_{fc}) and that at the permanent wilting point (θ_{pwp}) (see Liu *et al.*, 2017). PAW can only be realistically determined from measurements of the water potential (ψ) of the soil, after gravitational drainage (~0 kPa) and at θ_{pwp} (-1000 to -1500 kPa) (Figure 1). The permanent wilting point being where plant water availability terminates due to the high counter pressure required by roots to abstract it from the soil particle matrix, as determined by the soil matrix potential (ψ_m). The matrix properties of soils are altered by soil type, maturation/development and by management and they can all influence both total SWC and PAW (e.g. and possibly biochar application; see Figure 1). The importance of $\theta_{paw,}$ θ_{fc} and θ_{pwp} on crop physiological function (leaf growth and photosynthesis) and yield are well known (see Dunne *et al.,* 1975).

Less is known about the impacts that management practices, such as biochar application, have on soil function. But evidence suggests that the physical structure of biochar, with respect to its surface area (de Melo Carvalho *et al.,* 2014), its chemistry (Glaser *et al.,* 2002) and porosity and micro- and macro-structure (Downie *et al.,* 2009; Abel *et al.*, 2011; Kinney *et al*., 2012; Liu *et al*., 2017), or the physical properties of the soil itself (Castellini *et al*., 2015; Omondi *et al*., 2016), such as bulk density (Blanco-Canqui 2017) are altered [Table 2]. It is hypothesised that such features, particularly biochar's high internal porosity, has the potential to increase SWC which leads to greater PAW (Liu *et al*., 2017). Importantly for there to be evidence that biochar reduces crop drought stress an increase in PAW is required. If crop water availability were increased by biochar incorporation, then changes in PAW can only be effectively determined from measurements of the flux of water from the soil to the root. The energy gradient (soil matric potential, ψ_m) in the process, to overcome the forces required to remove water from within (capillary) and adhering (adsorption) to soil/biochar particles, has to be measured to determine PAW (Kramer 1969; Figure 1).

Is there evidence from *terra preta* soils of increasing plant available water?

Increasing soil organic matter (SOM) content enhances SWC and PAW which is a key factor in determining crop yields (Bates *et al.,* 2008). It has been shown that the original Amazonian *terra preta* soil patches have higher SWC relative to non-*terra preta* neighbouring soils (Lehmann *et al.,* 2003b and quoted within from Hartt 1885; Teixeira and Martins 2003; Glaser *et al.,* 2001; 2004). However, due to the complex composition of *terra preta*, it is an assumption that differences in SWC were only due to the presence of biochar. A number of non-peer reviewed studies, in Portuguese, describe many *terra preta* soil patches where soil 'moisture retention' was suggested as an important factor in explaining increased crop growth (see Kern *et al.,* 2003; Kampf *et al.,* 2003). The challenge in validating these reports is to determine how difference in SWC increase crop growth and if an increase in PAW can be measured. Glaser *et al.* (2004) compared *terra preta* soil patches with local native ferralsols and showed a 15% increase in topsoil SWC at 'field capacity', from which they conclude increased growth on *terra preta* was at least in part due to improved SWC, as may be the case elsewhere (McKey *et al.,* 2010). However, more recent observations on *terra preta*, generally, provide little experimental support for the notion of increases in PAW (Lehmann *et al.,* 2003b; 2009; Downie *et al.,* 2009). It is implied, via the benefits of increased SOM that PAW increases in *terra preta* soils (Lehmann *et al.,* 2003b; Major *et al.,* 2009). This speculative approach, with limited evidence is seen in the review of Jha *et al.,* (2010) where in the abstract, biochar increases in SWC are implicated despite only a single study being cited (i.e. that of Asia *et al.,* 2009).

Evidence for increases in SWC from biochar experiments using non-sandy soils

As has already been suggested there is a reasonable amount of reliable evidence to show that when soil texture is coarse and/or sandy biochar has the capacity, albeit at high application rates to increase SWC (see review of Blanco-Canqui 2017 and references above). There is a lack of evidence that increased plant growth on *terra preta* soil patches, is to increased PAW, however this does not mean that soil applied biochar does not increase PAW (Laird 2008; Verheijen *et al*., 2009; Jeffery *et al.,* 2011; Novak *et al*., 2012; Hardie *et al*., 2014; Omondi *et al*., 2016; Liu *et al*., 2017). From its physical structure, particularly its porosity, biochar has the ability to adsorb water and chemicals on its surface and retain water and gases in a manner proportionally linked to its structural pore geometry, size and pore size distribution (see Table 2; Dıaz-Teran *et al.,* 2001; Keech *et al.,* 2005; Pignatello *et al.,* 2006; Verheijen *et al*., 2009; Basso *et al*., 2013; Andrenelli *et al.,* 2016; Liu *et al.,* 2017). It is suggested that biochar pore sizes between 0.1 and 10 µm are responsible for biochar's water absorption (Major *et al*., 2009; Liu *et al*., 2016). Knowledge of biochar's direct effects on increasing SWC are not well documented (Abel *et al.*, 2013; Song and Guo 2012). For example, biochar's complex chemistry shows non-conventional hydrogen bonding of water molecules (Conte *et al.,* 2013). The evidence of an impact of applied charcoal to temperate soils is not extensive, but North American forest soils show increased soil 'available moisture' (increased by 18%) and reduced evaporation (Tryon 1948). What was meant by 'available moisture' was not defined. These differences were however detectable in sandy soils, used in an *in vitro* study, when mixture rates were high (45% by volume, which is equivalent to around 70 t ha^{-1} of biochar). As a soil management tool incorporation, at such a high rates, would be challenging for a number of reasons, beyond just the availability of sufficient feedstock. Chan *et al.* (2007) suggest that biochar increases SWC with applications >50 t ha^{-1}. They show measurements at field capacity, so it is unclear if PAW was increased and responsible for greater crop yields, particularly under drought; perhaps by temporal extension of water availability. A number of studies, similar to that of Chan *et al*. (2007), imply biochar enhanced SWC citing measurement of SWC (Song and Guo, 2012; Saarnio *et al*., 2013; Bruun *et al.,* 2014; Spokas *et al*., 2016; Omondi *et al*., 2016). While few studies show an increased yield response due to biochar in the absence of an increase in SWC; one exception is Graber *et al*. (2010), where biochar increased yields in the absence of a measurable change in SWC. Biochar application is suggested to increase water use efficiency (WUE), but the improvement was not shown to be due to less water being used, rather an increased yield with an absence of a link with water availability (Uzoma *et al.,* 2011). Similarly, work reported with dry land wheat strongly suggests that yield increases resulted from enhanced crop water uptake; however, neither SWC, nor crop water uptake data were presented (Blackwell *et al.,* 2010). A comparative study with sugarcane biochar (3% by weight), using soil (described as a heavy clay) filled lysimeters and field plots with biochar ploughed in (depth 0.3 m), suggested PAW increased due to biochar (Chen *et al.,* 2010). Initial differences in the moisture content of treated soil and controls soil were large (varying from 20% to 60%). There appeared to be an increase in SWC due to biochar, but this was only apparent with one biochar treatment. Measurements of SWC, during crop growth, showed differences which did not exceed 10% [by volume] (Chen *et al.,* 2010). To determine the impact of biochar (application rates of 100 to 200 t ha^{-1}) and irrigation on Quinoa physiology, plants were grown at 60% and 20% SWC (Kammann *et al.,* 2011). These experiments did not show to what extent the lower SWC treatment induced a decline in soil, or plant tissue water potentials. Nothing was presented of the effects of these treatments on crop leaf growth or transpiration, or how these processes may have adapted to compensate for the supply (root uptake) and demand (whole plant transpiration and/or plant leaf area) differences. Such differences can occur when irrigation is supplied at a constant rate (not plant demand driven) as with a gravimetric approach to controlling SWC (Kammann *et al.,* 2011).

More recent and generally more robust studies suggests that increased SWC, at field capacity, due to biochar incorporation, was only evident with sandy rather than clay type soils (Novak *et al.,* 2009; 2012; Uzoma *et al*., 2011; Abel *et al.,* 2013; Basso *et al.,* 2013; Mulcahy *et al.,* 2013; Bruun *et al*., 2014; Castellini *et al*., 2015; Haider *et al*., 2015; Jeffery *et al*., 2015; Laghari *et al.*, 2015; Obia *et al*., 2016; Glab *et al*., 2016; Omondi *et al*., 2016). Biochar addition to soil cores of different mineralogy, subject to a series of wetting and drying cycles, showed increased SWC (Herath *et al.,* 2013). But more importantly these authors quantified plant water availability by measuring SWC over a range of soil matric potentials (see Figure 1). Only from this approach can SWC measurements be functionally linked to PAW and the prediction of crop water availability over time.

Field based application and measurement of crop physiology and water balance

Biochar research urgently needs greater attention and precision in regard to the determination of its potential to increase crop yields, in the field, through measured changes in PAW (see approach and methodology in Liu *et al*., 2016). Karhu *et al.* (2011) were unable to demonstrate any biochar increases in yield, in an arable field crop rotation, when measuring SWC gravimetrically. However, in a meta-analysis of Omondi *et al*. (2016), which included some 274 studies, they determined available water derived from gravimetric measurements of SWC, produced a yield increase of 15% due to biochar (the sample size was 74). A large proportion of this yield increase came from laboratory compared to field experiments where coarse textured soils were used (sample size was 158). Elsewhere, it was suggested that biochar, with a single soil type (Maddock series), prolonged field crop water use over time (i.e. whole plant transpiration), but these data are not shown (Mollinedo *et al*., 2015). The work of Baronti *et al.* (2014) provides a link between crop physiology and soil and plant water relations. While the approach taken by Abel *et al.* (2013) showed an increase in SWC due to biochar use, albeit with a sandy soil. Similarly, the majority of references cited by Omondi *et al*. (2016), Blanco-Canqui (2017) and Ali *et al*. (2017) to support biochar induced reductions in plant drought stress were from sandy, or sandy loam soils. Similar measurements to those of Abel et al. (2013) have been used with a clay soil and show a rare level of published detail linking biochar application rate with positive and negative effects on the physical properties of a soil type of known limited porosity (Castellini *et al*., 2015). Andrenelli *et al.* (2016) suggested that the potential biochar induced increases in plant growth were achieved through changes in soil hydrology (due to soil bulk density declines), as well as, the biochar's own porosity (see Table 2). Measurements of soil volumetric water content (SVMC – g H_2O g^{-1} soil) derived from a fine-loamy Mollisols mixture showed no differences due to biochar application (Rogovski *et al*., 2014). Again, these authors suggest biochar porosity and high surface area were linked with increased crop yields. Their biochar experiments, despite measurements at a range of soil matric potential, and a suggested biochar increase in PAW over time, did not show a detectable biochar effect on maize yield in the presence of what is described as severe drought. In contrast Liu *et al*. (2016) analyses of biochar porosity and PAW showed that measurements at three pore sizes (diametric ranges <0.1 µm, 0.1-10 µm and 10-100 µm) where linked to field capacity as defined as water retained under pressure heads of -340 cm, 15 cm and 300 cm, respectively. It is the pores between 0.1 and 10 µm that enhance PAW. While Liu *et al*. (2017) demonstrated the experimental approach and value of PAW characterisation of biochar increased SWC using water retention curves (see Figure 1). The approach and the results, from this glasshouse study, to measure soil water retention, showed for one feedstock, that different rates of biochar pyrolysis increased PAW (Ojeda *et al.*, 2015).

Biochar structural porosity can increase SWC and potentially PAW and there is now good evidence that this feature can be manipulated by selection of biochar feedstock and by fine-tuning the pyrolysis process with respect to production temperature and duration. This opportunity facilitates the means by which biochar production can be manipulated to enhance SWC and PAW and produce ‘designer biochars’ which increased PAW.

Conclusions

This review has shown that increased attention is being given to measuring θ_{paw} (the difference between θ_{fc} and θ_{pwp}) derived from soil water potentials and how soil applied biochar contributes, to increasing PAW. Such knowledge is key to evaluating biochar as a management tool to sustain crop growth under conditions of water shortage. Some of the studies highlighted adopt appropriate metrics to determine changes in PAW which needs to be duplicated in future research. Evidence indicates, at least in sandy compared to loamy soils with their intrinsically lower θ_s values, that biochar can, under some circumstances increase PAW. The evidence suggests that extent to which biochar application could increase PAW is likely to be rate dependent. However, the practical and economic realism of achieving high rates of biochar application are a challenge. Knowledge of pyrolysis and the variation in feedstock structural and chemical types provides an opportunity to produce biochar with different physical (and chemical) characteristics to increase PAW. However, these characteristics and their potential to increase PAW need to be determined for a specific type of biochar, feedstock and pyrolysis process. As yet there is only limited evidence that field biochar application improves crop water availability and therefore crop yields, particularly in temperate regions. The link between crop water use and biochar has yet to be fully examined. The limited time span over which most biochar experiments are performed has unknown implications for understanding biochar's longer-term potential to sustain observed effects such as increased crop yields. This is particularly true considering biochar's recalcitrant and hydrophobic properties, along with those induced by mixing with soil (structural, physical, chemical and hydrological) and the impacts that may be seen on crop productivity. This review has shown why it is important to measure θ_{paw} when evaluating the possible benefits of biochar use in agriculture. It has also shown that the quantification of available water needs to be derived from measurement of ψ_m to account for differences in soil and biochar structure and function, physical and chemical, along with their interactions.

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References

Abel, S., Peters, A., Trinks, S., Schonsky, H., Facklam, M., & Wessolek, G. 2013. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. *Geoderma,* **202–203**, 183–191.

Ali, S., Rizwan, M., Qayyum, M.F., Ok, Y.S., Ibrahim, M., Riaz, M., Arif, M.S., Hafeez, F., Al-Wabel, M.I. & Shahzad, A.N. 2017. Biochar soil amendment on alleviation of drought and salt stress in plants: a critical review. *Environmental Science Pollution Research* **24**, 12700–12712

Andrenelli, M.C., Maienzab, A., Genesiob, L., Migliettab, F., Pellegrinia, S., Vaccarib, F.P., Vignozzia N. 2016. Field application of pelletized biochar: Short term effect on the hydrological properties of a silty clay loam soil. *Agricultural Water Management* **163**, 190-196.

Asai, H., Samson, B.K., Stephan, H.M., Songyikhangsuthor, K., Homma, K., Kiyono, Y., Inoue, Y., Shiraiwa, T. & Horie. T. 2009. Biochar amendment techniques for upland rice reproduction in Northern Laos: 1 Soil physical properties, leaf SPAD and grain yield. *Field Crop Research*, **111**, 81-84.

Atkinson, C.J., Fitzgerald, J.D. and Hipps, N.A. 2010. Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review. *Plant and Soil,* **337**, 1-18.

Baronti, S., Vaccari, F.P., Miglietta, F., Calzolari, C., Lugato, E., Orlandini, S., Pini, R., Zulian, C. & Genesio, L. 2014. Impact of biochar application on plant water relations in *Vitis vinifera* (L.). *European Journal of Agronomy*, **53**, 38–44.

Basso, A.S., Miguez, F.E., Laird, D.A., Horton, R. & Westgate, M. 2013. Assessing potential of biochar for increasing water holding capacity of sandy soils. *Global Change Biology Bioenergy*, **5**, 132-143.

Bates, B.C., Kundzewicz, Z.W., Wu, S., Palutikof, J.P. 2008. Climate Change and Water. 2 Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva. p. 210.

Biederman, L.A. & Harpole, S.W. 2013. Biochar and its effects on plant productivity and nutrient cycling: a meta-analysis. *Global Change Biology Bioenergy*, **5**, 202–214.

Blackwell, P., Krull, E., Butler, G., Herbert, A, & Solaiman, Z. 2010. Effect of banded biochar on dryland wheat production and fertiliser use in south-western Australia: an agronomic and economic perspective. *Australian Journal of Soil Research*, **48**, 531-545.

Blackwell, P., Riethmuller, G., Collins, M. 2009. Biochar application for soil. In: Lehmann J and Joseph S, editors. Biochar for Environmental Management Science and Technology. London: Earthscan. p. 207-226.

Blanco-Canqui, H. 2017.Boiochar and soil physical properties. *Soil Science Society of America Journal*, **81**, 687-711.

Brown, R.A., Kercher, A.K., Nguyen, T.H., Nagle, D.C. & Ball, W.P. 2006. Production and characterization of synthetic wood chars for use as surrogates for natural sorbents. *Organic Geochemistry*, 37, 321-333.

Bruun, E.W., Petersen, C.T., Hansen, E., Holm, J.K. & Hauggaard-Nielsen, H. 2014. Biochar amendment to coarse sandy subsoil improves root growth and increases water retention. *Soil Use and Management*, **30**, 109-118.

Castellini, M., Giglio, L., Niedda, M., Palumbo, A.D. & Ventrella, D. 2015. Impact of biochar addition on the physical and hydraulic properties of a clay soil. *Soil and Tillage Research*, **154**, 1-13.

Cayuela, M.L., van Zwieten, L., Singh, B.P., Jeffery, S., Roig, A., & Sanchez-Mondero, M.A. 2014. Biochar's role in mitigating soil nitrous oxide emissions: A review and meta-analysis. *Agriculture, Ecosystems and Environment*, **191**, 5-16.

Chan, K.Y., Van Zwieten, L., Meszaros, I., Downie, A. & Joseph, S. (2007) Agronomic values of green waste biochar as a soil amendment. *Australian Journal of Soil Research*, **45**, 629-634.

Chen, Y., Shinogi, Y. & Taira, M. 2010. Influence of biochar use on sugarcane growth, soil parameters, and groundwater quality. *Australian Journal of Soil Research*, **48**, 256-530.

Conte, P., Marsala, V., de Pasquale, C., Bubici, S., Valagussa, M., Pozzi A. & Alonzo, G. 2013. Nature of water-biochar interface interactions. *Global Change Biology Bioenergy*, **5**, 116-121.

DeLuca, T.H., MacKenzie, M.D., & Gundale, M.J. 2009. Biochar effects on soil nutrient transformation. In: Lehmann J, Joseph S. editors. Biochar for Environmental Management Science and Technology. London: Earthscan. p. 251-280.

de Melo Carvalho, M.T., de Holanda Nunes Maia, A., Madari, B.E., Bastiaans, L., van Oort, P.A.J., Heinemann, A.B., Soler da Silva, M.A., Petter, F.A., Marimon Jr, B.H. & Meinke, H. 2014. Biochar increases plant-available water in a sandy loam soil under an aerobic rice crop system. *Solid Earth* **5**, 939–952.

Dıaz-Teran, J., Nevskaia, D.M., Lopez-Peinado, A.J. & Jerez, A. 2001. Porosity and adsorption properties of an activated charcoal colloids and surfaces. *Physicochemical and Engineering Aspects*, **187–188**, 167–175.

Downie, A., Crosky, A. & Munroe, P. 2009. Physical properties of biochar. In: Lehmann J, Jospeh S, editors. Biochar for Environmental Management Science and Technology. London: Earthscan. p. 13-32.

Dunne, T., Moore, T.R. & Taylor, C.H. 1975. Recognition and prediction of runoff-producing zones in humid regions. *Hydrological Science Bulletin,* **20**, 305-326.

Forbes, M.S., Raison, R.J. & Skjemstad, J.O. 2006. Formation, transformation and transport of black carbon (charcoal) in terrestrial and aquatic ecosystems. *Science of the Total Environment*, **370**, 190-206.

Glab, T., Palmowska, J. & Gondek, K. 2016. Effect of biochar application on soil hydrological properties and physical quality of sandy soil. *Geoderma*, **281**, 11-20.

Glaser, B., Haumaier, L., Guggenberger, G. & Zech, W. 2001. The ‘Terra Preta’ phenomenon: a model for sustainable agriculture in the humid tropics. *Naturwissenschaften*, **88**, 37-41.

Glaser, B., Lehmann, J. & Zech, W. 2002. Ameliorating physical and chemical properties of highly weathered soils in the tropics with charcoal - a review. *Biology and Fertility of Soils*, **35**, 219-230.

Glaser, B., Guggenberger, G. & Zech, W. 2004. Identifying the Pre-Columbian Anthropogenic input on present soil properties of Amazonian Dark Earths (*Terra Preta*). In: Glaser B, Woods WI, Verlag S, Heidelberg B, editors. Amazonian Dark Earths: Explorations in Space and Time. Berlin: Springer.

Graber, E.R., Harel, Y.M., Kolton, M., Cytryn, E., Silber, A., David. D.R., Tsechansky, L., Borenshtein, M. & Elad, Y. 2010. Biochar impact on development and productivity of pepper and tomato grown in fertigated soilless media. *Plant and Soil*, **337**, 481–496.

Gray, M., Johnson, M.G., Dragila, M.I., & Kleber, M. 2014. Water uptake in biochars: The roles of porosity and hydrophobicity. *Biomass and Bioenergy*, 61, 196-205.

Haider, G., Koyro, H-W., Azam, F., Steffens, D., Müller, C. & Kammann, C. 2015. Biochar but not humic acid product amendment affected maize yields via improving plant-soil moisture relations. *Plant and Soil*, **395**, 141–157.

Hardie, M., Clothier, B., Bound, S., Lover, G. & Close D. 2014. Does biochar influence soil physical properties and soil water availability? *Plant and Soil*, **376**, 347-361.

Herath, H.M.S.K., Camps-Arbestain, M. & Hedley, M. 2013. Effect of biochar on soil physical properties in two contrasting soils: An Alfisol and an Andisol. *Geoderma*, **209–210**, 188–197.

Jay, C.N., Fitzgerald, J.D., Hipps, N.A. & Atkinson, C.J. 2015. Why short-term biochar application has no yield benefits: evidence from three field-grown crops. *Soil Use and Management*, **31**, 241–250.

Jeffery, S., Abalos, D., Prodana, M., Bastos, A.C., van Groenigen, J.W., Hungate, B.A. & Verheijen, F. 2017. Biochar boosts tropical but not temperate crop yields. *Environmental Research Letters*, **12 (5)**, 053001.

Jeffery, S., Meinders, M.B.J., Stoof, C.R., Bezemer M.T., van de Voorde, T.F.J., Mommer, L. van Groenigen, J.W. 2015. Biochar application does not improve the soil hydrological function of a sandy soil. *Geoderma,* 251-252, 47-54.

Jeffery, S., Verheijen, F.G.A., van der Velde, M. & Bastos, A.C. 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. *Agriculture, Ecosystems and Environment*, **144**, 175–187.

Jha, P., Biswas, A.K., Lakaria, B.L. & Rao, A.S. 2010. Biochar in agriculture – prospects and related implications. *Current Science*, **99**, 1218-1225.

Jien, S-H. & Wang, C-S. 2013. Effects of biochar on soil properties and erosion potential in a highly weathered soil. *Catena* **110**, 225-233.

Kammann, C.I., Linsel, S., Gobling, J.W. & Koyro, H-W. 2011. Influence of biochar on drought tolerance of *Chenopodium quinoa* Willd and on soil–plant relations. *Plant and Soil*, **345**, 195–210.

Kampf, N., Woods, W.I., Sombroek, W., Kern, D.C. & Cunha, T.J.F. 2003. Calssification of Amazonian dark earths and other ancient anthropic soils. In: Lehmann J, Kern DC, Glaser B, Woods WI, editors. Amazonian Dark Earths Origin Properties Management. Dordrecht: Kluwer Academic Publishers. p. 77-102.

Karhu, K., Mattila, T., Bergstrom, I. & Regina, K. 2011. Biochar addition to agricultural soil increased CH_4 uptake and water holding capacity – Results from a short-term pilot field study. *Agriculture, Ecosystems and Environment*, **140**, 309–313.

Keech, O., Carcaillet, C., Nilsson, M-C. 2005. Adsorption of allelopathic compounds by wood-derived charcoal: the role of wood porosity. *Plant and Soil*, **272**, 291–300.

Kern, D.C., D'Aquino, G., Rodrigues, E.T., Frazao, F.J.L., Sombroek, W., Myers, T.P. & Neves, E.G. 2003. Distribution of Amazonian dark earths in the Brazilian Amazon. In: Lehmann J, Kern DC, Glaser B, Woods WI, editors. Amazonian Dark Earths Origin Properties Management. Dordrecht: Kluwer Academic Publishers. p. 51-75.

Kinney, T.J., Masiello, C.A., Dugan, B., Hockaday, W.C., Dean, M.R., Zygourakis, K. & Barnes, R.T. 2012. Hydrologic properties of biochars produced at different temperatures. *Biomass and Bioenergy,* **41**, 34-43.

Kramer, P.J. (1969) Plant and soil water relationships: a modern synthesis. McGraw-Hill Book Company. New York, USA.

Laghari, M., Mirjat, M.S., Hu, Z., Fazal, S., Xiao, B., Hu, M., Chen, Z. & Guo, D. 2015. Effects of biochar application rate on sandy desert soil properties and sorghum growth. *Catena* **135**, 313-320.

Laird, D. 2008. The charcoal vision: a win–win–win scenario for simultaneously producing bioenergy, permanently sequestering carbon, while improving soil and water quality. *Agronomy Journal*, **100**, 178-181.

Laird, D. Fleming, P., Davis, D.D., Horton, R., Wang, B. & Karlen, D.L. 2010. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. *Geoderma*, **158**, 443-449.

Lehmann, J., da Silva Jr, J.P., Steiner, C., Nehls, T., Zech, W. & Glaser, B. 2003a. Nutrient availability and leaching in an archaeological Anthrosol and Ferralsol of the Central Amazon basin: fertilizer, manure and charcoal amendments. *Plant and Soil*, **249**, 343-357.

Lehmann, J., Grant, J. & Rondon, M. 2006. Biochar sequestration in terrestrial ecosystems – a review. *Mitigation, Adaptation and Strategies for Global Change*, **11**, 403-427.

Lehmann, J., Kern, D.C., German, L.A, McCann, J., Martins, G.C. & Moreira, A. 2003b. Soil fertility and production potential. In: Lehmann J, Kern DC, Glaser B, Woods WI editors. Amazonian Dark Earths: Origin, Properties, Management. Dordrecht: Kluwer Academic Publishers. p. 105-124.

Lehmann, J. & Rondon, M.A. 2005. Bio-char soil management on highly weathered soil in the humid tropics. In: Uphoff N, editor. Biological approaches to sustainable soil systems. Boca Raton. p. 517–530.

Lehmann, J., & Joseph, S. 2009. Biochar for Environmental Management, Science and Technology. London: Earthscan.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., O'Neill, B., Skjemstad, J.O., Thies, J., Luizao, F.J., Petersen, J. & Neves, E.G. 2006. Black carbon increases cation exchange capacity in soils. *Soil Science Society of America Journal*, **70**, 1719-1730.

Liu, C., Wang, H., Tang, X., Guan, Z., Reid, B.J., Rajapaksha, A.U., Ok, Y.S. & Sun, H. 2016. Biochar increased water holding capacity but accelerated organic carbon leaching from a sloping farmland soil in China. *Environmental Science Pollution Research*, **23**, 995–1006.

Liu, X., Zhang, A., Ji, C., Joseph, S., Bian, R. & Li, L. 2013. Biochar's effect on crop productivity and the dependence on experimental conditions—a meta-analysis of literature data. *Plant and Soil*, **373**, 583-594.

Liu, Z., Dugan, B., Masiello, C.A. & Gonnermann, H.M. 2017. Biochar particle size, shape, and porosity act together to influence soil water properties. PLOS One, 0179079.

Major, J., Steiner, C., Downie, A. & Lehmann, J. 2009. Biochar effects on nutrient leaching. In: Lehmann J, Joseph S. editors. Biochar for Environmental Management Science and Technology. London: Earthscan. p. 271-287.

McKey, D., Rostain, S., Iriarte, J., Glaser, B., Birk, J.J., Holste, I. & Renard, D. 2010. Pre-Columbian agricultural landscapes, ecosystem engineers, and self-organized patchiness in Amazonia. *Proceeding of the National Academy of Science*, **107**, 7823–7828.

Mollinedo, J., Schumacher, T.E. & Chintala, R. 2015. Influence of feedstocks and pyrolysis on biochar's capacity to modify soil water retention characteristics. *Journal of Analytical and Applied Pyrolysis,* **114**, 100-108.

Mukherjee, A., Zimmerman, A.R. & Harris, W.G. 2011. Surface chemistry variations among a series of laboratory-produced biochars. *Geoderma* **163**, 247-255.

Mulcahy, D.N., Mulcahy, D.L., Dietz, D. 2013. Biochar soil amendment increases tomato seedling resistance to drought in sandy soils. *Journal of Arid Environments*, **88**, 222-225.

Novak, J.M., Busscher, W.J., Watts, D.W., Amonette, J.E., Ippolito, J.A., Lima, I.M., Gaskin, J., Das, K.C., Steiner, C., Ahmedna, M., Rehrah, D. & Schomberg, H. 2012. Biochars impact on soil-moisture storage in an ultisol and two aridisols. *Soil Science*, **177**, 310-320.

Novak, J.M., Lima, I., Xing, B., Gaskin, J.W., Steiner, C., Das, K.C., Ahmedna, M., Rehrah, D., Watts, D.W., Busscher, W.J. & Schomberg, H. 2009. Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. *Annals of Environmental Science*, **3**, 195-206.

Obia, A., Mulder, J., Martinsen, V., Cornelissen, G. & Borresen, T.Y. 2016. 2016. In situ effects of biochar on aggregation, water retention and porosity in light-textured tropical soils. *Soil and Tillage Research*, **155**, 35-44.

Ojeda, G., Mattana, S., Avila, A., Alcaniz J.M., Volkmann, M. & Bachmann, J. 2015. Are soil–water functions affected by biochar application? *Geoderma* **249-250**, 1-11.

Omondi, M.O., Xia, X., Nahayo, A., Liu, X., Korai, P.K. & Pan, G. 2016. Quantification of biochar effects on soil hydrological properties using meta-analysis of literature data. *Geoderma*, **274**, 28-34.

Pressler, Y., Foster, E.J., Moore, J.C. & Cotrufo, M.F. 2017. Coupled biochar amendment and limited irrigation strategies do not affect a degraded soil food web in a maize agroecosystem, compared to the native grassland. *Global Change Biology Bioenergy*, **9**, 1344-1355.

Pignatello, J.J., Kwon, S. & Lu, Y. 2006. Effect of natural organic substances on the surface and adsorptive properties of environmental black carbon (Char): attenuation of surface activity by humic and fulvic acids. *Environmental and Science Technology*, **40**, 7757-7763

Richter, D.D. & Babbar, LI. 1991. Soil diversity in the tropics. *Advances in Ecological Research*, **21**, 315-389.

Rogovska, N., Laird, D., Rathke, S.J. & Karlen, D.L. 2014. Biochar impact on Midwestern Mollisols and maize nutrient availability. *Geoderma* **230-231**, 340-347.

Saarnio, S., Heimonen, K. & Kettunen, R. 2013. Biochar addition indirectly affects N_2O emissions via soil moisture and plant N uptake. *Soil Biology and Biochemistry*, **58**, 99-106.

Shinogi, Y. & Kanri, Y. 2003. Pyrolysis of plant, animal and human waste: physical and chemical characterization of the pyrolytic products. *Bioresource Technology*, **90**, 241–247.

Song, W. & Guo, M. 2012. Quality variations of poultry litter biochar generated at different pyrolysis temperatures. *Journal of Analytical and Applied Pyrolysis*, **94**, 138–145.

Spokas, K.A., Weis, R., Feyereisen, G., Watts, D.W., Novak, J.M., Lim, T.J. & Ippolito, J.A. 2016. Biomass or biochar – which is better at improving soil hydraulic properties? *Acta Horticulturae*, **1146**, 235-242

Steiner, C., Teixeira, W.G., Lehmann, J., Nehls, T., de Macedo, J.L.V., Blum, W.E.H. & Zech, W. 2007. Long term effects of manure, charcoal and mineral fertilization on crop production and fertility on a highly weathered Central Amazonian upland soil. *Plant and Soil* 2007, **291**, 275-290.

Steiner, C., Das, K.C., Garcia, M., Forester, B. & Zech, W. 2008. Charcoal and smoke extract stimulate the soil microbial community in a highly weathered xanthic Ferralsol. *Pedobiologia*, **51**, 359-366.

Teixeira, W.G. & Martins, G.C. 2003. Soil physical characterization. In: Lehmann J, Kern DC, Glaser B, Woods WI, editors. Amazonian Dark Earths Origin Properties Management. Dordrecht: Kluwer Academic Publishers. p. 271-286.

The Royal Society (2009a). Geoengineering the climate science, governance and uncertainty. RS Policy Document 10/09.The Royal Society, London. ISBN 978-0-85403-773-5.

The Royal Society (2009b). Reaping the benefits: science and the sustainable intensification of global agriculture. RS Policy Document 11/09.The Royal Society, London. ISBN 978-0-85403-784-1.

Tryon, E.H. 1948. Effects of charcoal on certain physical, chemical and biological properties of forest soils. *Ecological Monographs*, **18**, 82-115.

Uzoma, K.C., Inoue, M., Andry, H., Fujimaki, H., Zahoor, A. & Nishihara, E. 2011. Effect of cow manure biochar on maize productivity under sandy soil condition. *Soil Use and Management*, **27**, 205–212.

Verheijen, F.G.A., Jeffery, S., Bastos, A.C., van der Velde, M., and Diafas, I. 2009. Biochar Application to Soils - A Critical Scientific Review of Effects on Soil Properties, Processes and Functions. EUR 24099 EN, Office for the Official Publications of the European Communities, Luxembourg, 149pp.

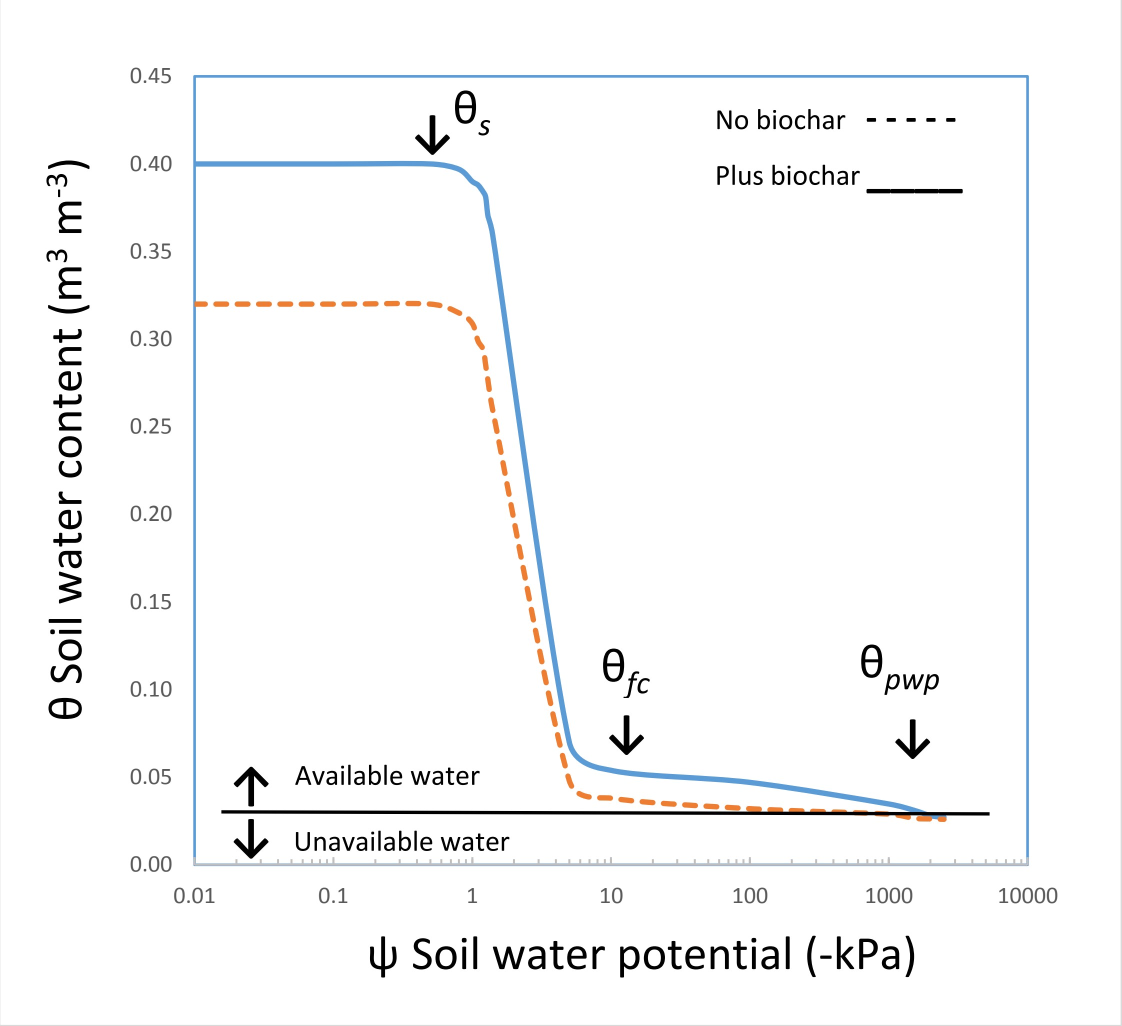
Woolf, D., Amonette, J.E., Street-Perrott, F.A., Lehmann, J. & Joseph, S. 2010. Sustainable biochar to mitigate global climate change. *Nature Communications*, 1:56. DOI: 10.1038/ncomms1053.

Zhang, D., Yan, M., Niu, Y., Liu, X., van Zwieten, L., Chen, D., Bian, R., Cheng, K., Li, L., Joseph, S., Zheng, J., Zhang, X., Zheng, J., Crowley, D., Filley, T.R. & Pan, G., 2016. Is current biochar research addressing global soils constraints for sustainable agriculture? *Agriculture, Ecosystems and Environment*, **226**, 25-32.

Zong, Y., Xiao, Q. & Lu, S. 2016. Acidity, water retention, and mechanical physical quality of a strongly acidic Ultisol amended with biochars derived from different feedstocks. *Journal of Soils and Sediments* **16**, 177-190.

Figure 1. Soil moisture release/retention curve characteristic changes described by the relationship between soil volumetric content (θ) and soil water potential (ψ) describing the hypothetical effects of the application of biochar.

The example here with a sandy soil type shows that volumetric water content declines sharply as the matrix soil water potential becomes more negative. At lower soil water potentials the material can hold a volume of water that is unavailable for crops. The black horizontal line denotes the point at which, with respect to a plant θ_{pwp} *where the remaining soil water is not theoretically available. The position of this line will move upwards in soils with a higher clay and/or organic matter content, as will the value of* θ_s*.*



Note: The relationships shown are derived from the principles of hydrology for a sandy type soil and are supported by the work of Gray et al., 2014; Rogovska et al., 2014; Andrenelli et al., 2016.

Table 1. Soil factors altered by the presence of biochar within a sandy or loamy/clay type soil. Both indirect and direct factors are presented for both typical soil types and an assessment is made based on the literature read and all those cited in this review.

Predicted significant of enhanced plant available water (PAW)	Presence of evidence for an impact in a sandy type soil	Factor influenced by the presence of biochar in the soil	Presence of evidence for an impact in a loamy/clay type soil
Predominantly indirect effects		*Soil physical properties*	
	+++	Increase in carbon storage (*true with most soils except peat soils*)	+
	+++	Enhanced organic matter content (*assuming some biochar decomposition*)	-
	++	Reduction in bulk density (*due to biochar's low density*)	+
	+	Increased aeration/reduced soil anoxia (*due to soil aggregate mixing*)	++
		Soil microbial properties	
	+++	Provision of microbial refugia (*due to biochar porosity*)	++
	++	Increase in microbial diversity (*due to biochar porosity habitat creation*)	+
	++	Increase in microbial function	+
		Plant/crop properties	
	+	Enhanced volume of exploitation by root (*due to soil structural changes*)	-
Primarily direct effects		*Soil physical properties*	
	+	Enhanced water infiltration (*due to increased soil hydraulic conductivity*)	+++
	+++	Increased soil water content at saturation (*due to soil/biochar water absorption*)	+
	++	Increased soil water content at field capacity (*due to biochar water absorption*)	+
		Soil chemical properties	
	+++	Increased nutrients derived from biochar decomposition (*due to biochar's innate chemistry*)	+
	++	Enhanced nutrient adsorption on to biochar (*due to biochar's CEC*)	++
	++	Increased nutrient availability (*due to biochar's nutrient exchange properties*)	+
	+++	Reduced soil nutrient leaching (*due to biochar's nutrient retention properties*)	++
		Plant/crop properties	
	++	Increased root proliferation (*due biochar's physical and chemical properties*)	-
	+	Reduced plant oxidative stress (*due to biochar's absorption properties*)	+
	++	Conservation of soil water (*due to biochar's prolonged water availability for plant survival*)	+
	+	Increased crop water use efficiency (*due to biochar's capacity to store water longer*)	+
	++	Increased crop yields (*due to some or all of the above*)	+

Note: the assessment scouring annotation is a follows: very limited evidence of an influence (-), some evidence (+), reasonable evidence (++); and a good deal of evidence (+++). The categories are assigned based on estimation of numbers of papers published which show appropriate evidence and range from 0-1, 2-5, 6-10 and >10 respectively for each of the categories - to +++

Table 2. Classification of biochar pore structure revised from gas adsorption porosity and presented in relation to soil water holding capacity and biochar function

	Gas adsorption convention		Convention appropriate for use with biochar						
	Pore descriptor	Size distribution (μm)	Revised classification	Size distribution (μm)	Contribution to biochar porosity and surface area	Origin	Importance to soils	Manipulation	Source citation
Intra-particle pores	Micropores	<0.002	Pyrogenic nanopores (intrapores)	0.002 (<2 nm)	Majority of particle surface area.	Pyrogenically produced voids in the carbon matrix	Nutrient and chemical adsorption	Pyrolysis final temperature	Brown *et al*., 2006 Downie *et al*., 2009 Mukherjee *et al*., 2011 Gray *et al*., 2014
	Mesopores	0.002-0.05		(2-50 nm)	Major contribution to pore volume	Feature of the feedstock material	Determinant of PAW	Feedstock and the pyrolysis process	Downie *et al*., 2009 Gray *et al*., 2014 Liu *et al.* 2017
	Macropores	>0.05	Residual macropores (intrapores)	1-100 (>50 nm)	Major contributor to pore volume. Contains water when the soil θ_s	Feature of the feedstock material	Aeration, hydrology and a habitat for microorganisms (bacteria, fungi 0.5–5 μm)	Selection of biochar feedstock	Downie *et al*., 2009 Major *et al.* 2009 Liu *et al*., 2016
Inter-particle pores			Inter aggregates pores. External pores between soil and biochar particles	Determined by soil texture >500	Determines SWC at higher soil ψ	Soil structure and biochar shape and size	Root development, hydrology and aeration	Improvements by changes in biochar soil aggregate mix ratio and biochar pyrolysis rate	Rogovska *et al*. 2014 Andrenelli *et al*., 2016 Liu *et al*., 2017

Note: the approach tabulated here is derived from sources cited in the right-hand column