3. EFFECTS ON SOIL PROPERTIES, PROCESSES AND FUNCTIONS

This chapter discusses the effects of biochars with different characteristics (Chapter 2) on soil properties and processes. First, effects on the soil properties are discussed, followed by effects on soil physical, chemical and biological processes. The agricultural aspect of the production function of soil is reviewed in detail (including meta-analyses)

3.1 Properties

3.1.1 Soil Structure

The incorporation of biochar into soil can alter soil physical properties such as texture, structure, pore size distribution and density with implications for soil aeration, water holding capacity, plant growth and soil workability (Downie et al., 2009). Particularly in relation to soil water retention, Sohi et al. (2009) propose an analogy between the impact of biochar addition and the observed increase in soil water repellency as a result of fire. Rearrangement of amphiphilic molecules by heat from a fire, as proposed by Doerr et al. (2000), would not affect the soil, but could affect the biochar itself during pyrolysis. In addition, the soil hydrology may be affected by partial or total blockage of soil pores by the smallest particle size fraction of biochar, thereby decreasing water infiltration rates (see Sections 3.1.1 and 3.2.3). In that sense, further research aiming to fully evaluate the extent and implications of biochar particle size distribution on soil processes and functioning is essential, as well as its influence on biochar mobility and fate (see Section 3.2.1).

3.1.1.1 Soil Density

Biochar has a bulk density much lower than that of mineral soils and, therefore, application of biochar can reduce the overall bulk density of the soil, although increases in bulk density are also possible. If 100 t ha^{-1} of biochar with a bulk density of 0.4 g cm^{-3} is applied to the top 20 cm of a soil with a bulk density of 1.3 g cm^{-3}, and the biochar particles do not fill up existing soil pore space, then the soil surface in that field will be raised by *ca.* 2.5 cm with an overall bulk density reduction (assuming homogeneous mixing) of 0.1 g cm^{-3} to 1.2 g cm^{-3}. However, if the biochar that is applied has a low mechanical strength and disintegrates relatively quickly into small particles that fill up existing pore spaces in the soil, then the dry bulk density of the soil will increase.

In agronomy, relatively small differences in soil bulk density can be associated with agronomic benefits. Conventionally, i.e. without biochar additions, lower bulk density is associated with higher SOM content leading to nutrient release and retention (fertiliser saving) and/or lower soil compaction due to better soil management (potentially leading to improved seed germination and cost savings for tillage and cultivation). Biochar application to soil by itself may improve nutrient retention directly (see Section 3.2.2), but nutrient release is mostly very small (except for some biochars in the first years, especially in ash-rich biochars) and the application of biochar with heavy machinery may compact the subsoil, depending on the application method and timing

Soil compactibility is closely related to soil bulk density. Soane (1990) reviewed the effect of SOM, i.e. not including biochar, on compactibility and proposed several mechanisms by which SOM may influence the ability of the soil to resist compactive loads:

1) Binding forces between particles and within aggregates. Many of the long-chain molecules present in SOM are very effective in binding mineral particles. This is of great importance within aggregates which "…are bound by a matrix of humic material and mucilages" (Oades in Soane, 1990).
2) Elasticity. Organic materials show a higher degree of elasticity under compression than do mineral particles. The relaxation ratio – R – is defined as the ratio of the bulk density of the test material under specified stress to the bulk density after the stress has been removed. Relaxation effects of materials such as straw are therefore much greater than material like slurry or biochar.
3) Dilution effect. The bulk density of SOM is usually appreciably lower than mineral soil. It can however differ greatly, from 0.02 t m^{-3} for some types of peat to 1.4 t m^{-3} for peat moss, compared to 2.65 t m^{-3} for mineral particles (Ohu et al. in Soane, 1990).
4) Filament effect. Roots, fungal hyphae and other biological filaments have the capacity to bind the soil matrix.
5) Effect on electrical charge. Solutions/suspensions of organic compounds may increase the hydraulic conductivity of clays by changing the electrical charge on the clay particles causing them to move closer together, flocculate and shrink, resulting in cracks and increased secondary – macro - porosity (Soane, 1990). Biochar's ash fraction could cause similar effects.
6) Effect on friction. An organic coating on particles and organic material between particles is likely to increase the friction between particles (Beekman in: Soane, 1990). The direct effect of biochar on soil friction has not been studied.

The effect of biochar application on soil compactibility has not been tested experimentally yet. From the above mechanisms, however, direct effects of biochar are probably mostly related to bullet points 3, 5 and 6 above. The very low elasticity of biochar suggests that resilience to compaction, i.e. how quickly the soil 'bounces back', is unlikely to be increased directly by biochar. The resistance to compaction of soil with biochar could potentially be enhanced via direct or indirect effects (interaction with SOM dynamics and soil hydrology). For example, some studies have shown an increase in mycchorizal growth after additons of biochar to soil (see Section 3.2.6) while under specific conditions plant productivity has also been shown to increase (see Section 3.3). The enhanced development of hyphae and roots will have an effect on soil compaction However, experimental research into the mechanisms and subsequent modeling work is required before any conclusions can be drawn regarding the overall effect of biochar on soil compaction.

3.1.1.2 Soil pore size distribution

The incorporation of biochar into soil can alter soil physical properties such as texture, structure, pore size distribution and density with implications for soil aeration, water holding capacity, plant growth and soil workability. The soil pore network can be affected by biochar's inherent porosity as well as its other characteristics, in several ways. Biochar particle size and pore size distribution and connectivity, the mechanical strength of the biochar particles, and the translocation and interaction of biochar particles in the soil are all determining factors that will lead to different outcomes in different soil-climate-management combinations. As described in the above section, these factors can cause the overall porosity of the soil to increase or decrease following biochar incorporation into soils.

There is evidence that suggests that biochar application into soil may increase the overall net soil surface area (Chan et al., 2007) and consequently, may improve soil water retention (Downie et al., 2009; see Section 3.1.2) and soil aeration (particularly in fine-textured soils; Kolb, 2007). An increased soil-specific surface area may also benefit native microbial communities (Section 3.2.6) and the overall sorption capacity of soils (Section 3.2.2). In addition, soil hydrology may be affected by partial or total blockage of soil pores by the smallest particle size fraction of biochar, thereby decreasing water infiltration rates (see Sections 3.1.1, 3.1.2 and 3.2.3). Nevertheless, experimental evidence of such mechanisms is scarce and, therefore, any effects of the pore size distribution of biochar on soil properties and functions is still uncertain at this stage. Further research aiming to fully evaluate the extent and implications of biochar particle size distribution on soil processes and functioning is essential, as well as its influence on biochar mobility and fate in the environment (see Section 3.2.1).

Table 3.1 shows the classifications of pore sizes in material science and soil science. Fundamental differences, i.e. orders of magnitude difference for classes with the same names, are obstacles in communicating to any audience outside of biochar research and also hinder the communication efficiency within interdisciplinary research groups that work on biochar in soils. Therefore, it is recommended that existing classifications are modified to resolve this confusion. However, in this review we will use the existing terminology and the relevant classification will need to be retrieved from the context.

Table 3.1 Pore size classes in material science *vs.* soil science

	Material science	**Soil science**
	Pore size (µm)	
Cryptospores	na	<0.1
Ultramicropores	na	0.1-5
Micropores	<0.002	5-30
Mesopores	0.002-0.05	30-75
Macropores	>0.05	>75

be the key for the model output to resemble the botanic evidence for climate-vegetation interactions in mid-Holocene North Africa. Model simulations with a darker soil colour led to an intensified monsoon which brought precipitation further north; testifying the importance of changes in soil albedo on climate feedbacks.

The principle that biochar application to soils decreases the albedo of bare soil and thereby contributes to further warming of the planet is accepted, however, if, and where, that would lead to an effect of relevant magnitude is much less certain. Bare soil is limited to the winter months on fields growing spring crops, or in orchards without ground cover (e.g. olive orchards, vineyards). In the former case, the warming effect may be relatively small because solar radiation reaching the surface is low in winter months, however, many orchards and vineyards are in more southern parts that receive a greater solar input and the bare soil conditions persist throughout the year. Post et al. (2000) investigated the influence of soil colour and moisture content on the albedo of 26 different soils ranging widely in colour and texture. They found that wet samples had their albedo reduced by a mean of 48% (ranging between 32-58%), and that Munsell colour value is linearly related to soil albedo.

The amount of solar radiation that reaches the soil surface (as affected by sun angle and slope and vegetation cover) and the specific heat of soils, largely control the rate at which soils warm up in the spring, and thus influence the emergence of seedlings. Soil colour and soil moisture content are the main factors determining the specific heat of soil. For pure water the specific heat is about 4.18 J g^{-1} K^{-1}; that of dry soil is about 0.8 J g^{-1} K^{-1}. Therefore, although soils high in biochar content are usually dark in colour, if the biochar increases the water retention of the soil concomitantly (see Section 3.1.2) then the associated extra energy absorption is countered by a high water content, which causes the soil to warm up much more slowly (Brady, 1990). This implies that biochar with low water retention capacity (e.g. because of water repellent properties, see Section 3.1.2.1) will cause the greatest increase in soil warming, and that this impact will be greatest where biochar is applied to light-coloured soils (high Munsell value) with spring crops (i.e. bare soil in spring) or orchards/vineyards.

3.1.4 CEC and pH

The cation exchange capacity (CEC) of soils is a measure for how well some nutrients (cations) are bound to the soil, and, therefore, available for plants uptake and 'prevented' from leaching to ground and surface waters. It is at negatively charged sites on the reactive surface area of biochar (and clay and organic matter) where cations can be electro-statically bound and exchanged. Cations compete with each other as well as with water molecules and can be excluded when the pore size at the charged site is smaller than their size. Cheng et al. (2006) assessed the effects of climatic factors on biochar oxidation in natural systems. The CEC of biochar was correlated to the mean temperature and the extent of biochar oxidation was related to its external surface area, being seven times higher on the external surfaces than in its interior (Cheng et al., 2008). It is not known at present how the CEC of biochar will change as the biochar disintegrates by weathering and tillage operations, ‘ages’ and moves through the soil.

Anions are bound very poorly by soils under neutral or basic pH conditions. This is one of the reasons why crops need fertilising, as anionic nutrients (e.g. phosphates) are leached or flushed from the soil into ground/surface waters (eutrophication). Cheng et al. (2007) found biochar to exhibit an anion exchange capacity (at pH 3.5) which decreased to zero as it aged in soil (over 70 years). If biochar can play a role in anion exchange capacity of soils remains an unanswered question and a research effort is required into the mechanisms to establish under what conditions (e.g. more neutral pH) anions may be retained.

As previously discussed, biochar pH is mostly neutral to basic (see Table 2.2). The liming effect has been discussed in the literature as one of the most likely mechanisms behind increases in plant productivity after biochar applications, and the meta-analysis in this report (Section 3.3) provides supporting evidence for that mechanism. Lower pH values in soils (greater acidity) often reduce the CEC and thereby the nutrient availability. In addition, for many of the tropical soils studied, reduced aluminium toxicity by reducing the acidity is proposed as the most likely chemical mechanism behind plant productivity increases.

For the experimental studies used in the meta-analysis on plant productivity (see Section 3.3.1) the average pre-amendment soil pH was 5.3 and post-amendment 6.2, although for poultry litter biochar on acidic soils the change was as large as from pH 4.8 to 7.8. Therefore, a scientific consensus on a short term liming effect of biochar applied to soil is apparent. This implies that biochars with greater liming capacity can provide greater benefit to arable soils that require liming, by being applied more frequently at lower application rates. Thereby reducing, or potentially cutting, a conventional liming operation, and hence providing a clear cost saving.

3.2 Soil Processes

3.2.1 Environmental behaviour, mobility and fate

An effective evaluation of biochar stability in the environment is paramount, particularly when considering its feasibility as a carbon sequestration tool. A sound understanding of the contribution that biochar can make to improve soil processes and functioning relies on knowing the extent and implications of the changes biochar undergoes in soil over time. Such knowledge remains, however, sparse and most experimental evidence has been gathered for other forms of black carbon. Energy-dispersive X-ray spectrometry looks promising as a tool for providing evidence of such changes in soil (Glaser et al., 2000; Brodowski et al., 2005a).

Current evaluations of the age of black carbon particles from both wildfires and anthropogenic activity indicate great stability of (at least) a significant component of biochar, ranging from several millennia to hundreds of years (e.g. Skjemstad et al., 2001; Lehmann et al., 2009). Such stability has been employed as a tool for evaluating, dating and modelling of ancient cropping

	Increases in mycorrhizal abundace which is linked to observed increases in plant productivity	Possibly due to: a) alteration of soil physico-chemical properties; b) indirect effects on mycorrhizae through effects on other soil microbes; c) plant–fungus signalling interference and detoxification of allelochemicals on biochar; or d) provision of refugia from fungal grazers (3.2.6)
	Increases in earthworm abundance and activity	Earthworms have been shown to prefer some soils amended with biochar than those soils alone. However, this is not true of all biochars, particularly at high application rates (3.2.6)
Negatives	The use of biochar analogues for assessing effects of modern biochars is very limited	Charcoal in Terra Preta soils is limited to Amazonia and have received many diverse additions other than charcoal. Pyrogenic BC is found in soils in many parts of the world but are of limited feedstock types and pyrolysis conditions (Chapter 1)
	Soil loss by erosion	Top-dressing biochar to soil is likely to increase erosion of the biochar particles both by wind (dust) and water. Many other effects of biochar in soil on erosion can be theorised, but remain untested at present (4.1)
	Soil compaction during application	Any application carries a risk of soil compaction when performed under inappropriate conditions. Careful planning and management could prevent this effect (4.6)
	Risk of contamination	Contaminants (e.g. PAHs, heavy metals, dioxins) that may be present in biochar may have detrimental effects on soil properties and functions. The ocurrence of such compounds in biochar is likely to derive from either contaminated feedstocks or the use of processing conditions that may favour their production. Evidence suggests that a tight control over the type of feedstock used and lower pyrolysis temperatures (<500°C) may be sufficient to reduce the potential risk for soil contamination (3.2.4)
	Residue removal	Removal of crop residues for use as a feedstock for biochar production can forego incorporation of the crop residue into the soil, potentially leading to multiple negative effects on soils (3.2.5.5)
	Occupational health and fire hazards	Health (e.g. dust exposure) and fire hazards associated to the production, transport, application and storage of biochar need to be considered when determining the suitability for biochar application. In the context of occupational health, tight health and safety measures need to be put in place in order to reduce such risks. Some of these measures have already proved adequate (5.2)
	Reduction in earthworm survival rates (limited number of cases)	High biochar application rates of >67 t ha^{-1} (produced from poultry litter) were shown to have a negative effect on earthworm survival rates, possibly due to increases in pH or salt levels (3.2.6)
Unknown	Empirical evidence is extremely scarce for many modern biochars in soils under modern arable management	Biochar analogues do not exist for many feedstocks, or for some modern pyrolysis conditions. Biochar can be produced with a wide variety of properties and applied to soils with a wide variety of properties. Some short term (1-2 yr) evidence exists, but only for a small set of biochar, environmental and soil management factors and almost no data is available on long term effect (1.2-1.4)
	C Negativity	The carbon storage capacity of biochar is widely hypothesised, although it is still largely unquantified and depends on many factors (environmental, economic, social) in all parts of the life cycle of biochar and at the several scales of operation (1.5.2 and Chapter 5)
	Effects on N cycle	N_2O emissions depend on effects of biochar addition on soil hydrology (water-filled pore volume) and associated microbial processes. Mechanisms are poorly understood and thresholds largely unknown (1.5.2)
	Biochar Loading Capacity (BLC)	BLC is likely to be crop as well as soil dependent leading to potential incompatibilities between the irreversibility of biochar once applied to soil and changing crop demands (1.5.1)
	Environmental behaviour	The extent and implications of the changes that biochar undergoes in soil remain largely unknown. Although biochar physical-chemical