NRC Research Press
REVIEW

Biochar influences on agricultural soils, crop production, and the environment: A review

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Abstract: Given its high pore volume and adsorption capacity, and when applied as an agricultural soil amendment, its ability to enhance the soil's nutrient- and water- holding capacities, biochar has become a focus of research interest. In most applications, crop productivity is significantly increased after agricultural soils are amended with biochar. In addition to increasing soil quality, the biochar amendments sequester carbon within the soil. However, the long-term effects of amending agricultural soils with biochar are difficult to predict, because the mechanisms behind the increase in productivity of biochar amended soils are not yet fully understood. Long-term detrimental effects on soil and the environment can occur if biochar is applied haphazardly. Current knowledge and the additional experimental work required to thoroughly understand the influence of biochar amendment on the behavior of agricultural soils processes are reviewed. Further, studies on the post production processing of biochar are discussed in the context of the possible engineering of biochar for particular states of soil degradation.

Key words: biochar production, post-production, soil physical properties, fertility, crop production, carbon sequestration.

Résumé : Étant donné son volume de pores élevé et sa capacité d'adsorption, et lorsqu'appliqué comme un amendement de sol agricole, sa capacité à améliorer la substance nutritive du sol et sa capacité de rétention d'eau, le biocharbon fait l'objet d'intérêt en recherche. Dans la plupart des applications, la productivité des cultures agricoles a augmenté de façon significative après que les sols agricoles soient amendés au moyen du biocharbon. En plus d'augmenter la qualité du sol, les amendements au biocharbon séquestrent le carbone dans le sol. Cependant, les effets à long terme de l'amendement des sols agricoles au moyen du biocharbon sont difficiles à prévoir, car les mécanismes sous-jacents à l'augmentation de la productivité des sols amendés par le biocharbon ne sont pas encore entièrement compris. Les effets néfastes à long terme sur le sol et l'environnement peuvent se produire si le biocharbon est appliqué de façon fortuite. On fait le point sur les connaissances actuelles ainsi que le travail expérimental supplémentaire requis afin de bien comprendre les effets de l'amendement au biocharbon sur le comportement des processus des sols agricoles. De plus, on analyse les études sur le traitement post-fabrication du biocharbon dans le cadre de l'ingénierie du biocharbon aux fins d'états particuliers de dégradation du sol. [Traduit par la Rédaction]

Mots-clés : fabrication de biocharbon, post-fabrication, propriétés physiques du sol, fertilité, cultures agricoles, séquestration de carbone.

Introduction

"Terra Preta" refers to a particularly fertile anthropogenic soil discovered near the ruins of a pre-Columbian civilization located in the Amazon basin. This soil contrasts sharply with typical Amazonian jungle soils, which are often nutrient deficient. The nutrient poor soils are the result of excessive rain dissolving nutrients from the topsoil and precipitating them into deeper soil strata, subsurface environments which are inaccessible to rooting crops. Some two thousand years ago the current Terra Preta soils were generated by enrichment of the native jungle soils with a carbonaceous material (Glaser and Birk 2012). Terra Preta soils have remained highly fertile and crops used to grow vigorously in them because they harbor large microbial communities (Kim et al. 2007). The indigenous Terra Preta people produced these carbonaceous materials by burying biomass in pits, where they smoldered and decomposed for days (Johannes et al. 2015) although this is still conjecture.

Nowadays, researchers are trying to mimic "Terra Preta" by applying biochar (charcoal-like material) to agricultural soils. Amendment of soils with biochar is considered both as a way of building the soil's organic fraction and as a means to sequester carbon (C). There are more than 2500 articles on the effect of biochar on agricultural soil processes and crop production published between 2009 and the present; the number of studies before 2009 is very small. This growing interest indicates that amending the soil with biochar is likely to become a commonplace practice. However, accurately predicting the total behavior of biochar-amended agricultural soils remains problematic. It is virtually impossible to remove the biochar once it has been applied to a soil, because it is chemically very inert (Johannes et al. 2015). Given the irreversibility of biochar applications, and their undocumented but potential detrimental effects on crops and on human health, their impacts on soil processes should be carefully assessed.

Biochar amendment of soils also raises interest with respect to climate change mitigation. As biochar locks up carbon during its production process, the carbon release to the atmosphere might be reduced by sequestering the biochar in soils and thus reducing our current release of greenhouse gases (GHGs) (Hansen et al. 2015). The objectives of this literature review are to highlight the current knowledge of biochar's characteristics and their influences on the amended soils' physicochemical properties and their longer term effects on soil processes and the environment.

Received 23 January 2016. Accepted 22 June 2016.

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Environ. Rev. **24**: 495–502 (2016) dx.doi.org/10.1139/er-2016-0008

Table 1. Influence of biomass feedstock and pyrolysis temperature on biochar surface area and pore volume

Feedstock	Pyrolysis temperature (°C)	Pore volume (cm^3/g)	Surface area (m^2/g)	References
Malt spent Rootlets	400	3.4	0.016	Manariotis et al. (2015)
	800	340	0.21	
Hardwood	300	0.06	N/A	Xiao and Pignatello (2015)
	500	0.21	N/A	
Wheat	400	0.016	10.15	Manna and Singh (2015)
	600	0.034	20.38	
Biosolids	650	N/A	395	Kaudal et al. (2015)
Wood	350	N/A	1	Brewer et al. (2014)
	800	N/A	317	
Rice husk	350	N/A	32.7	Claoston et al. (2014)
	650	N/A	261.72	
Empty fruit bunch	350	N/A	11.76	
	650	N/A	28.2	
Rubber wood	300	0.0034	1.399	Shaaban et al. (2014)
	700	0.0097	5.49	
Medicinal herbs	300	4.45	0.0075	Yuan et al. 2014
	700	11	0.0178	
Coal tailings	400	N/A	2.7	Tremain et al. (2014)
	800	N/A	75.3	
Pine needle	100	N/A	0.65	Tang et al. (2013)
	700	N/A	490.8	
Cotton seed hulls	350	N/A	4.7	
	800	N/A	322	
Oakwood	350	N/A	450	
	600	N/A	642	
Corn Stover	350	N/A	293	
	600	N/A	527	
Broiler litter manure	350	N/A	59.5	
	700	N/A	94.2	
Soybean stalk	300	N/A	144.17	
	700	N/A	250.23	
Pine needles	300	N/A	4.09	Ahmad et al. (2013)
	700	N/A	390.52	
Sewage sludge	400	N/A	33.44	Méndez et al. (2013)
	600	N/A	37.18	
Switchgrass	450	N/A	5.89	Kim et al. (2013)
	800	N/A	52.27	
Bagasse	400	0.03	14.4	Kameyama et al. (2012)
	800	0.16	219	
Switchgrass	250	N/A	0.4	Ippolito et al. (2012)
	500	N/A	62.2	
Maize	300	N/A	1	Wang et al. (2015)
	600	N/A	70	

Note: N/A, data not available.

Biochar production

Biochar can be produced by the pyrolysis of biomass material in the absence of oxygen at temperatures in the range of 250 °C to 700 °C (Yuan et al. 2014). The raw material or the feedstock for biochar production can originate from a variety of biomass types including wood, woodchips, crop residues, manure, and other animal wastes. The efficacy of biochar for soil amendment depends on the type of feedstock used and the pyrolysis conditions used (Table 1). Both the feedstock properties and the pyrolysis conditions contribute to the biochar's characteristics including the chemical composition, surface chemistry, nutrient composition, adsorption capacity, cation exchange capacity (CEC), pH, and the physical structure (Cimò et al. 2014). The physical characteristics of biochar including the pore number and size are also influenced by the biochar processing conditions (Ronsse et al. 2013). For example, the biochar produced at temperatures exceeding 450 °C and then added to soil may improve the internal drainage of the soil and render the water available to plants, whereas a soil amended with a biochar produced at lower temperature (<450 °C) sometimes repels water (Page-Dumroese et al. 2015).

Biochar created at temperatures less than 300 °C contain cellulose compounds, because higher temperatures break down the structure and chemistry of such cellulose compounds (Antal and Gronli 2003). Therefore, the soil amendments using biochar produced at lower temperatures retains more soil nutrients because they contain more surface area for nutrient to be adsorbed (nutrient retention sites) (Glaser et al. 2002). On the other hand, the porosity of biochar increases with the temperature of pyrolysis due to the volatilization of tars present within the pores and the escape of gases at the higher pyrolysis temperatures (Cantrell et al. 2007).

Processing of biochar

Biologically-activated biochar

For biochar to become biologically active and enrich the soil, it needs to be activated, such that the particle surface area is increased and the pores are opened, and become a medium for beneficial soil microorganisms. Activation of biochar in soils occurs naturally and it can take from months to years to complete. During this time, biochar may increase the soil's ability to adsorb and retain nutrients and water, thereby making these resources more available to the plants (Cross and Sohi 2013). The natural process of biochar activation in soils can be sped up by mixing biochar with compost or manure (Dias et al. 2010; Jindo et al. 2012). It has been found that the biochar generated at lower temperatures and which has not received further activation or processing will have lesser adsorption capacity and surface area than biologically activated biochar (Plaza et al. 2014). The surface area of non-activated biochar is approximately 10 $m^2 kg^{-1}$ compared to 200–1000 $m^2 kg^{-1}$ for activated biochar (Dehkhoda et al. 2016).

Chemically activated biochar

Numerous methods are available for activating the freshly produced biochar. Activating biochar to generate greater absorption capacity requires specific catalytic chemicals, such as potassium hydroxide (KOH), to be loaded onto the carbon surfaces of biochar. The residual carbon in activated biochar is porous but has a low surface area. To generate a large surface area, a second thermal treatment in the presence of chemicals is applied to biochar after pyrolysis. This is often followed by a washing step using water to remove the activating chemicals or the unwanted ash from the activated biochar (Kirk et al. 2012). Another way of activating biochar is to use sewage sludge or zinc chloride to enhance the surface area (Chen et al. 2002). Comparatively, the biochar activated using undigested sludge has greater carbon content, lesser ash content, greater surface area, and better phenol adsorption characteristics than the biochar activated using inorganic chemicals (Tay et al. 2001).

Alternatively, the room temperature treatment of biochar using organic acids has been shown to be an effective way to rapidly oxidize its surface, thereby significantly increasing the number of acidic oxygenated groups (e.g., carboxylic acid groups) on the surface. Carboxylic acid groups are essential in improving a biochar's nutrient holding capacity (Park et al. 2013). Polarizing the acidic nature of oxidized biochar will be suited for the retention of basic ions such as ammonium (NH_4^+) and other cations. A strong correlation exists between the quantity of NH_4^+ adsorbed by the oxidized biochar and the concentration of acid groups on biochar (Kastner et al. 2012). Due to the extra step required to biologically-activate the biochar, in some cases, it would not be economical to use biochar for soil amendment (Kuppens et al. 2014).

Fortifying biochar with nutrients

Hydrogen sulfide (H_2S) is a toxic gas present in biogas, which increases the rate of corrosion in engines using biogas. This corrosion may be prevented by separating and removing H_2S from the biogas (Powell et al. 2012). In turn, H_2S can biologically activate biochar, wherein the surface of the activated biochar serves as a site where the H_2S is completely converted into elemental sulfur and sulfate compounds. Such a system provides an environmentally sustainable method for disposing of H_2S from agricultural soils (RiceCenter 2012). Camphor-derived biochar resulting from pyrolysis under temperatures varying between 100 and 500 °C have been shown to be effective in H_2S sorption. Pyrolysis temperature and surface pH were the production variables showing significant influence on H_2S sorption capacity of biochar (Shang et al. 2012). Given their greater surface area, activated carbon shows greater adsorption and retention of sulfur, and additional heat treatment further enhanced their capacity for the adsorption and retention of sulfur (Wenguo et al. 2005). These observations are helpful for designing biochar as an engineered sorbent for the removal of H_2S from biogas production units.

Biochar pelletizing

Pelletizing biochar might lead to specifically engineering biochar for a particularly degraded soil and in reducing its dustiness (Andrenelli et al. 2016 and Karl and Alzena 1990). Handling and applying biochar to soils poses a health risk associated with inhaling small airborne particles of biochar. Pellets not only reduce dust but also gives the product a uniform shape and size thus allowing the biochar to be more uniformly distributed in the soil (Reza et al. 2011).

Earlier attempts to pelletize biochar using binders without wood flour failed to yield a cohesive pellet (Dumroese et al. 2011). The addition of binders like starch and polylactic acid (PLA) to achieve biochar pellet integrity could provide more resistance to stresses developed during the water sorption and swelling of biochar in the soil (Dumroese et al. 2011). Similarly, adding canola oil at a rate of 3% by mass improved the rheology of the blend, pellet output rate, and integrity (Dumroese et al. 2011). Most research in pelletizing biochar has focused on densifying pellets to obtain higher packing efficiencies. However, the less dense the pellet, the greater will be the swelling coefficient of biochar pellet. During pellet formation, use of a large die diameter and shorter die length could reduce pellet density, but maintaining biochar porosity (Reza et al. 2014). The biochar pellets can be amended with nutrients to further enhance the pellet's performance as a soil amender. Biochar pellets have been produced by blending and pelletizing switchgrass (*Panicum virgatum* L.) biochar, lignin, and potassium (K) and phosphorus (P) fertilizers (Kim et al. 2014).

Future studies on the use of additives to biochar to increase the coherence and resistance of the pellets for better transportation and application to soils are required. The best pretreatment conditions for making coherent biochar pellets should be assessed by measuring (1) the pellets' resistance to abrasion and immersion, (2) their modulus of elasticity, and (3) the uniformity in pellet's moisture content. Calculations of the modulus of elasticity and compressibility of biochar pellets are needed to develop analytical standards. Similar to manure, minerals, and compost, the efficiency of soil amendment material varies according to how they are applied and incorporated into the soil (e.g., surface applied, banded, or broadcasted). Biochar application techniques, especially with pelletized biochar, should be investigated to achieve the highest possible application efficiency.

Influence of biochar addition to agricultural soils

Biochar amendments alter the physicochemical properties of soils, including bulk density, porosity, CEC, and pH (Atkinson et al. 2010). It also influences soil processes, such as water- and nutrient- holding capacities and consequently influences the crop production.

Soil–biochar mix and its physical characteristics

The average density of biochar particles measures less than that of the soil particles (Sharma et al. 2014). Consequently, adding biochar decreases the bulk density of the soil. The soils with lower bulk density reduce the energy requirement of mechanical tillage (Carter 1990). However, when fine particles of biochar are applied, or when the larger biochar particles disintegrate in arable soils under the influence of tillage and cultivation operations (Wang et al. 2013), the disintegrated fine particles can fill up small pores in the soil leading to increased bulk density in the biochar–soil mix. Biochar particle size is likely to be reduced by mechanical disturbances such as plowing in agricultural areas or by freeze–thaw cycles (Saran et al. 2009). Little has been published about the agricultural practices that could affect the biochar particle's degradation, where small biochar fractions also might lead to the closing of the soil pores and lead to the formation of a subsurface hardpan (Verheijen et al. 2010). Roots elongation and proliferation are affected by mechanical impedance within the soils. Denser soil will increase the mechanical impedance, decrease root growth, and reduce crop productivity (Otto et al. 2011). An obvious risk of soil compaction occurs through the very application of biochar itself. If biochar is applied using heavy machinery while the water-filled soil pores are near saturation, the risk of compaction increases (Carlos et al. 2012).

In soils vulnerable to compaction, positive and (or) negative consequences in adding biochar may occur, both in the topsoil and subsoil. Biochar has a diminished elasticity, as measured by the relaxation ratio which is the ratio of the bulk density of the test material under a specified stress to the bulk density after the stress has been removed. Comparatively, straw has a greater elasticity ratio, and when the straw is charred and applied as biochar, the resilience of the soil to compaction loads decreases.

Biochar amendments alter soil porosity and increase the soil surface area. A soil–biochar mix tends to improve the soil's water-holding capacity (WHC) (Basso et al. 2013). A comparison of soil water retention curves has shown an increase in the soil WHC with the application of biochar (Abel et al. 2013). Nevertheless, this additional water held by the soil may not be readily available to the plants, because the water in the very small saturated pores is too tightly held against the plant's uptake forces (Sohi et al. 2010). As the percentage of biochar increases, so does the total volumetric water content, largely due to the alteration of micropores in the soil (Ngelique 2011). In a study by Ventura et al. (2013), biochar produced from vegetable bio-products and applied to soil at a rate of 60 Mg ha^{-1} showed inconsistencies in the soil's water retention capability. These inconsistencies were attributed to the soil non-homogeneity in porosity and to the method by which soil samples were prepared. In the laboratory, large soil samples in the pressure plate apparatus reduced this uncertainty. Also, the hydrophobicity of biochar might also have had an influence on the results. Biochar produced at temperatures higher than 400 °C have greater infiltration and water retention at their saturation point than the biochar produced at lower temperatures. This might be attributable to high biochar production temperatures influencing biochar pore volume and pore tortuosity (Kameyama et al. 2014). Soil hydrology is affected by the reductions in organic matter resulting from intensive agricultural practices (Laird et al. 2010). Studies have shown that, applying biochar to the sandy soil at a rate of 60 Mg ha^{-1} resulted in a significant increase in soil water retention capacity, which was attributed to the biochar's porous structure (Ulyett et al. 2014). In a study by Kameyama et al. (2014), a biochar amendment at a rate of 5 t ha^{-1} increased the water retention in sandy loam soil, resulted in a 12% reduction in the cumulative evaporation ($\mathrm{kg_{water}/m^2_{soil}}$) from the soil. Further, the sandy loam soil's water holding capacities at saturation and the field capacity relatively increased by 30% and 16%, respectively.

Soil water content increased with an increase in the quantity of biochar added to the soil (Ibrahim et al. 2013). The soil amended with woodchip biochar had greater water content than the soil amended with dairy manure biochar (Lei and Zhang 2013). The biochar produced from dairy manure or woodchips and mixed at 5% dry weight basis (d.w.b) with soil, led to an increase in hydraulic conductivity (k_{sat}) of the amended soils. The k_{sat} of the soil amended with woodchip biochar was greater than the soil amended with dairy manure biochar. This was attributed to the high ash content of woodchip biochar (Lei and Zhang 2013). Generally, the changes in electrical charge on the clay particles cause rearrangement of the structure, increase in secondary macroporosity, and an increase in k_{sat} of the soils.

Biochar produced at pyrolytic temperatures less than 450 °C contain more water repelling organic compounds (Kinney et al. 2012; Yi et al. 2015), which may lead to reduced plant growth in the soils (Fang et al. 2014). This hydrophobicity of biochar may also lead to soil erosion due to increased water overflow. The hydrophobicity of biochar can be controlled by appropriate selection of feedstock and pyrolytic conditions. If necessary, post-pyrolysis treatments can be used to decrease biochar hydrophobicity (Yi et al. 2015).

Systems and methods, such as using artificially aged soil–biochar mix, are required to be developed that mimic the long-term behavior of the soil amended with biochar (Song et al. 2013), to understand how the physical nature of the biochar influences the soil processes over time; and also to investigate the effect of different biochar feedstocks, pyrolysis conditions, biochar application rates, different soil types, environmental and agricultural conditions on the responses of biochar addition to the soil. However, at present, controlled long-term studies are not available in the literature. Moreover, conservation methods, such as no-till, cover crops, complex crop rotations, mixed farming systems, and agroforestry, are needed to be considered with the biochar amendment to the soil. The effects of biochar amendment to the soils that are prone to compaction and its consequent influence on the soil processes and root systems have not been investigated. Similarly, the effects of biochar on friction and cohesion between the soil particles and the biochar have not been fully quantified. Very little information is available on how the large-scale addition of biochar to the soil impacts the frequency and the intensity of irrigation. Soil hydrology may also be affected by the partial or the total blockage of soil pores by the smallest particle size fraction of biochar that decreases the water infiltration into the soil. Thus, the biochar application can be beneficial or detrimental depending on the particle size of the biochar and on the texture of the soil.

Soil–biochar mix fertility

The difference in chemical composition of biochar and the soil (Yuan et al. 2016) has an impact on plant growth due to the alteration in soil chemistry and changes in the availability of nutrients to the roots. Biochar derived from animal wastes had significantly increased the soil's pH and CEC from acid-free drained soils (Uzoma et al. 2011; Wang et al. 2014).

Biochar adsorbs soil nutrients, decreases their leaching into groundwater (Kameyama et al. 2012), and makes them readily available to plants (Rogovska et al. 2014). On the other hand, if biochar is incorporated without activation into the soil, its high adsorption capacity will result in the adsorption and fixing of available nutrients from the soil, thereby barring the crops from soil nutrients. Thus, an initial inhibition of crop growth might occur immediately after the amendment of agricultural soils with inactivated biochar (Lehmann et al. 2011).

Microorganisms have higher reproductive and retention rates in biochar amended (versus non-amended) soils (Lehmann et al. 2011). Microorganisms housed in biochar's micropores multiply more rapidly as they are sheltered from their predators. Apparently, the soil organic matter and microbial activity were enhanced due to the high pore structure of biochar and the presence of degradable components in the biochar. Thus, biochar is a binding agent that improves the soil macro-aggregates (Lu et al. 2014).

To conclude, the general relationship between the soil organic content, the type of biochar amendment required and the resulting crop yield is poorly understood. The investigation to comprehend the correlation between the effects of changes in soil physical properties on the change in soil chemistry, such as oxidation of nutrients due to increased porosity of soil–biochar mix, should receive more attention to quantify the physicochemical behavior of the soil–biochar mix.

Crop production in soil–biochar mix

A number of studies have reported positive effects of biochar amendment on crop productivity (Wang et al. 2012; Baronti et al. 2014; Revell et al. 2012; Uzoma et al. 2011; Jeffery et al. 2011; Galinato et al. 2011; Blackwell et al. 2010; Graber et al. 2010; Asai et al. 2009; Hossain et al. 2010). Statistical meta-analysis showed that the biochar amendment resulted in an increase in crop productivity, as high as 13%, in acidic and neutral pH soils where the biochar amendment increased the pH value of the soil (liming effect) and led to a greater crop productivity (Hass et al. 2012). Application of biochar produced from flax straw fines to loamy soils at a rate of 1 t ha^{-1} had shown significant effects on wheat growth (Ahmed and Schoenau 2015).

Crop production increase in soils with a coarse or medium texture and amended with biochar was due to the improved WHC and nutrient availability of the soil (Jeffery et al. 2011). Plants exhibit thinner and more extensively branched roots in the soils with increased biochar amendment, due to the soil's increased WHC and the reduced leaching of nitrogen (N) and phosphorus (P) from the soil (Bruun et al. 2014; Ventura et al. 2013).

Given the great variety of biochar feedstocks available, along with the changes in inherent biophysical characteristics and agronomic practices of different study sites, it is difficult to generalize the benefits from biochar amendment. In experimental field trials, it is often difficult, or impossible, to control all the environmental variables, especially the variability in meteorological factors. This can lead to weakness in the data obtained from such experiments, and reduce accuracy when extrapolating the results to other environmental conditions. Therefore, more scientific evidences regarding effects of biochar on soil processes are highly needed before a developed policy of large-scale implementation can be proposed.

Environmental implications of biochar production and application to agricultural soils

Decomposition of biochar in soil

Interest has grown in biochar application to soils not only for its benefits as an organic fertilizer but also for the need to address the climate change (Woolf et al. 2010). If organic wastes (OW) are left to decompose naturally, they release carbon into the atmosphere in the form of CO_2, which is one of the GHGs (Thomazini et al. 2015). Due to the lack of oxygen in the pyrolysis process, the carbon from the OW is locked away into the biochar. Thus, applying the biochar to the soil sequesters carbon and thus decreases the emission of GHGs into the atmosphere (Zhang et al. 2016).

Biochar amended soils contain as much as 35% d.w.b soil organic carbon (SOC) in the form of biochar (McHenry 2011). Inorganic nitrogen in the biochar amended soils comes from minerals and is added to soil through precipitation, or as fertilizers.

Biochar is considered highly resistant to biological degradation, because of the presence of aromatic carbon in its composition. The reported residence time for wood-derived biochar in the soil before complete degradation is in the range of 1000–12 000 years (Woolf et al. 2010). Biochar produced at low temperatures is less stable and could return significant amounts of carbon to the atmosphere within a few hundred years after it is added to the soil (Kinney et al. 2012). More research is needed to optimize the temperature and residence time during the pyrolysis process to produce biochar not only with a high aromatic carbon content but also make them stable in soils.

Biochar applied to the surface soil relocates to subsoil through tillage, as well as due to shrinkage-swelling of the soil (Eckmeier et al. 2007). Laboratory-based studies using freshly-made biochar tend to show some mass loss — sometimes quite large — over a period of days to years. Estimation of the long-term stability of biochar in soils based on the measurable short-term decomposition suggests that the biochar comprises both stable and degradable components (Kimetu and Lehmann 2010).

Combustion conditions during pyrolysis as well as the type of feedstock are influential in determining the proportion of labile and stable components in the biochar products (Singh et al. 2012). Measuring the influence of biochar production process on the properties of biochar is essential for the optimization of pyrolysis conditions for maximum net carbon sequestration (Alvarez et al. 2014). The chemical composition of biochar confers its high level of stability and is reflected in its elemental composition: highly aromatic and with a very high carbon content (Quilliam et al. 2013). It is likely that biochar stability is associated with its physical properties and structure. If the biotic and abiotic processes determining the fate of biochar are the same as those for other soil organic matter, higher soil temperature, moisture availability, lower clay content, and intensive tillage will accelerate its decomposition rate (Mašek et al. 2013).

Estimation of soil production of carbon dioxide is essential in assessing the quantity of carbon losses to the atmosphere from the soil (Saran et al. 2009). Since the measurement of the total quantity of soil carbon in an area is difficult and expensive due to its variability and complexity, the practical way to study the effect of various agronomic treatments on soil carbon content is through computer modeling. Assessing the potential impact of amending agricultural soils with biochar on environmental risk and sustainability of agricultural soils amended with biochar, with simulation models is lacking in the literature. If the dynamics of biochar are quantified then the rate and mode of application of biochar to soil can be optimized.

To conclude, biochar loss and mobility through the soil profile and into the water resources have not been researched adequately and transport mechanisms are very unclear. More research should be done to enable the prediction of likely rates of breakdown of biochar in soil. At the moment, there is insufficient data in the literature to compare the responses between short- and long-term stability under different climates and in different soil types. Therefore, the possible effects of biochar addition to soil on the environmental and human health are not fully understood.

Suppression of greenhouse gas release from the soil

Biochar application reduces the emission of nitrous oxide (N_2O) and CO_2 from soils and thus reduces the overall emission of greenhouse gases (GHG) into the atmosphere (Woolf et al. 2010). Shrub willow biochar decreased N_2O and CH_4 fluxes from loamy soils (Hangs et al. 2016). Moreover, the soil aeration which increases following the biochar amendment to soil contributes in suppressing the soil N_2O from releasing into the atmosphere (Case et al. 2012; Suddick and Six 2013). Cumulative N_2O production was consistently suppressed by at least 50% when a soil was amended with hardwood biochar at a rate of 22 Mg ha^{-1} (Case et al. 2012). The microbial or physical immobilization of nitrate (NO_3^-) in soil following the biochar addition may significantly contribute to the suppression of soil N_2O emissions. However, the enhancement of soil aeration by biochar incorporation made only a minimal contribution to the suppression of N_2O emissions from a sandy loam soil. The suppression of N_2O emissions from soil might be due to the biochar increasing soil aeration at relatively high moisture contents by increasing the soil's WHC (Van et al. 2009). However, when biochar is applied to soil it initially leads to the decomposition of soil organic matter and hence increases the CO_2 release to the atmosphere (Augustenborg et al. 2012). The net suppression and release of GHGs from soil have not fully been quantified.

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