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USE OF BIOCHAR AS A SOIL AMENDMENT: A BRIEF REVIEW

USO DEL BIOCARBÓN COMO ENMENDADOR DE SUELOS: UNA BREVE REVISIÓN

Cristina Muñoz[1*], Sergio Góngora[1], and Erick Zagal[1]

[1] Department of Soils and Natural Resources, Faculty of Agronomy, Universidad de Concepción, Vicente Mendez Avenue 595, Chillán, Chile.
* Corresponding author E-mail: cristinamunoz@udec.cl

RESUMEN

La degradación de los suelos es el resultado de factores naturales y antropogénicos, causando un fuerte impacto sobre la sustentabilidad agrícola, la calidad ambiental y aspectos sociales (pobreza) y políticos de la sociedad humana. La recuperación de suelos degradados puede ser a través de la promoción de un adecuado uso del suelo y prácticas de manejo conservacionistas, generando efectos de ganancia-ganancia en términos económicos y beneficios ambientales, tales como mayor agro-biodiversidad, mejor conservación y manejo ambiental y el incremento del secuestro de carbono (C). Una alternativa para mejorar la calidad del suelo es a través de aplicaciones de biocarbón. El objetivo de esta revisión fue analizar los cambios en las propiedades de suelos enmendados con biocarbón, determinando que el uso de este producto es una promisoria alternativa, porque puede mejorar algunas propiedades del suelo, como incrementos del pH en suelos ácidos, capacidad de intercambio catiónico y porosidad, y disminución de la densidad del suelo, mientras que también sirve como microhábitat para microrganismos del suelo. Sin embargo, el efecto sobre la emisión de gases de efecto invernadero (GHG) no ha sido dilucidado todavía, con contradictorios resultados dependiendo del suelo y sistema de cultivo.

Palabras claves: secuestro de C, pirólisis, propiedades biológicas del suelo, calidad de suelo, enmiendas orgánicas.

ABSTRACT

Soil degradation can be driven by either natural or anthropogenic causes and it can have strong impacts on agricultural sustainability, environmental quality, social issues (poverty) and political aspects of human society. Restoration of degraded soils could be through the promotion of improved land use systems and conservation management practices, that can have win-win effects in terms of economic and environmental benefits, such as greater agro-biodiversity, improved conservation and environmental management, and increased carbon (C) sequestration. An alternative to improve soil quality is the application of biochar. The aim of this review was to analyze changes in the properties of soils amended with biochar, determining that the use of this product is a promissory alternative because it can improve some soil properties, such as increased pH in acidic soils, cation exchange capacity and porosity and decreased bulk density, while it can also act as a microhabitat to soil microorganisms. However, the effect on greenhouse gas (GHG) emission has been not elucidated yet, with contradictory results depending on soil type and crop systems.

Key words: C sequestration, pyrolysis, biological soil properties, soil quality, organic amendment.

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INTRODUCTION

Soil degradation reduces the amount of organic matter and nutrients and limits its production (Ekholm and Lehtoranta, 2012), which can be reversed by using adequate soil management practices and optimizing land use systems. The improvement of soil organic carbon (SOC) is a management practice that has a positive effect on the physical, chemical and biological properties of the soil. It increases soil fertility by adding organic matter to the soil (Plante et al., 2007). It also reduces greenhouse gas emissions (GHG) to the atmosphere because soil can act as a C sink by storing C in soil depth and it can also be a C source, with emissions to the atmosphere as CO_2 (aerobic respiration) and/or in the form of CH_4 (anaerobic respiration) (Lal et al., 2006; Lemke and Janzen, 2007; Muñoz et al., 2010; 2011b). This double role of surface soils depends on different factors, where the difference between labile and stable organic material added is relevant since the latter contributes directly to increasing soil C sequestration (Lal et al., 2006). In this sense, the use of biochar (BC), which is a stable C type produced by controlled pyrolysis process, has been considered as a promissory alternative in recent decades because it provides different benefits in terms of physical, chemical and biological properties of the soil, contributing to soil remediation and climate change mitigation (Lehmann et al., 2003; 2006; Wolf et al., 2010). The aim of this brief review is to analyze the changes in soil properties (chemical, physical and biological) with the use of biochar as a soil amendment.

Soil degradation

Soil erosion might release organic carbon in the atmosphere and trigger climate warming (Reay et al., 2007; Dotterweich, 2008). Soil restoration techniques to increase soil organic matter (SOM) and stabilization of soil carbon (C) are required to increase productivity and improve environmental quality (Cantón et al., 2011).

Soil degradation has several causes and origins, being erosion considered as the main agent of environmental degradation in agricultural areas in the world. Improper use of soil and inadequate management, as well as the lack of appropriate technology, are key issues on this respect (Den Biggelaar et al., 2004; Cantón et al., 2011; Sun et al., 2014). Soil erosion causes the removal of sediment deposits, which are rich in organic matter and nutrients. When these sediments reach lakes or rivers, they enhance growth of aquatic plants, increase oxygen requirements, and decrease light transmission in deep waters, with the consequent eutrophication of the systems (Ekholm and Lehtoranta, 2012). In terms of soil properties, soil degradation reduces aggregate stability, alters size pore distribution and water availability, accelerates loss of nutrients specially C, N and phosphorous (P) and, consequently, reduces soil productivity (Den Biggelaar et al., 2004; Dotterweich 2008; Romero-Díaz et al., 2012).

Restoration of degraded soils caused by inadequate land use/management could be reversed through the promotion of improved land use systems and land management practices. These can provide win-win effects in terms of economic gains and environmental benefits: greater agro-biodiversity, improved conservation and environmental management and increased carbon sequestration (FAO, 2014). SOC is a key factor that influences both crop productivity and soil quality. It also has a positive effect on biological, physical and chemical properties, increasing fertility, especially in volcanic soils (Matus et al., 2006; Zagal et al., 2012).

Degraded soils have a great potential to increase C stock with the use of adequate managements practices. This results in a new steady state in the system, where time to reach this new equilibrium depends on soil, climate, land use and management practices (Cerri et al., 2006). For example, Xie et al. (2013) determined that a severely eroded red soil in subtropical China presented a rapid accumulation of SOC at 1 m of depth with afforestation (24 years after plantation), increasing 10 times its C content (from 13 Mg C ha^{-1} in control soil to 130.1 Mg C ha^{-1}). When studying a degraded land from the Mediterranean zone of Chile, Muñoz et al. (2007) determined that the presence of *Acacia caven* Mol. shrubs increased 25% the C stock in the profile (0-40 cm of depth) compared to intercanopy. Results of this study (Muñoz et al., 2007) and those reported by Stolpe et al. (2008) indicate that the management of the shrub vegetation of this savannah-type ecosystem presents a high potential in terms of C sink that contributes to atmospheric CO_2 reduction.

Biochar production

Application of by-products produced by environmentally-friendly industrial and agricultural systems can be considered as soil amendment materials. Composting from diverse organic materials (D'Hose et al., 2014; Weber et al., 2014), humic acid and water treatment residuals (Mukherjee et al., 2014) are example of amendments with several beneficial effects on soil. However, labile organic matter contained in these organic materials produce an intensive C mineralization (recorded as CO_2 emissions), releasing a considerable amount of nitrogen into the soil, but with a low amount of N uptake by plants. Recently, Weber et al. (2014) reported that less than 7% of the applied nitrogen from municipal waste compost was uptake by plants, while considerable amounts of N_2O were emitted into the atmosphere. Based on these results (Weber et al., 2014) and those reported by other authors (e.g., Webb et al., 2014; Long et al., 2015), the use of more stable C-applications could be considered as an alternative to decrease the risk of pollution in the ecosystems.

In this sense, thermal decomposition of organic material under limited supply of oxygen (O_2) combined with relatively low temperatures (less than 700°C) produce a carbon-rich product named biochar (Lehmann and Joseph, 2009). Despite the fact that the use of biochar in agricultural soils is an ancient practice, known through Amazonian Dark Earths or 'Terra preta do Indio' in the Amazon Basin of Brazil (Sombroek et al., 2003), it has gained importance only in recent years. Biochar is produced through the pyrolysis process using different organic materials, such as agricultural and forestry residues, organic residues and sludge, under oxygen limited conditions.

The concept of biochar is different from other products such as 'charcoal', which is used as fuel for heating, filter, industrial reductant or coloring agent, or 'black carbon', which includes all C-rich residues from fire or heat. Biochar is defined as C-rich products deliberately applied into the soil with the purpose of improving soil properties (Lehmann and Joseph, 2009). In recent years, biochar has positioned itself as a material with diverse applications in several disciplines. This has given rise to an International Biochar Initiative (IBI; www.biochar-international.org/publications/IBI) aimed at compiling information and research conducted worldwide on diverse agronomical and environmental uses to standardize biochar production and its evaluation. IBI generates guidelines to standardize the production and testing of biochar for soil use (IBI, 2014).

Pyrolysis can be classified as fast, intermediate and slow, depending on the operating conditions used. It corresponds to the thermal decomposition of organic materials at partial or total absence of oxygen resulting in three output streams: solid (biochar), bio-oil and gas (synthesis gas) (Fig. 1). However, production of biochar strengthens with a slow process of carbonization (Rodríguez, 2010), and its physicochemical properties, e.g. pH, surface area and essential elements content, can vary according to the feedstock type and pyrolysis conditions, such as temperature, heating rate, pressure and pre and post-treatment conditions, among others (Verheijen et al., 2010; González et al., 2013).

In terms of market activity, nearly all enterprises focus on biochar end use as a soil amendment (Jirka and Tomlinson, 2014). At international level, a promissory and growing market of biochar is being developed. Most of biochar companies are located in North America, Europe, Oceania, Asia, and Africa (but none in Latin America), and biochar is mainly sold (pure and blended biochar) through specialized retail stores. The price of biochar ranges from $US 0.08 to 13.48 per kg (not including any shipping or handling costs or value-added tax, VAT), with the lowest price being reported in the Philippines and the highest in the USA (Jirka and Tomlinson, 2014).

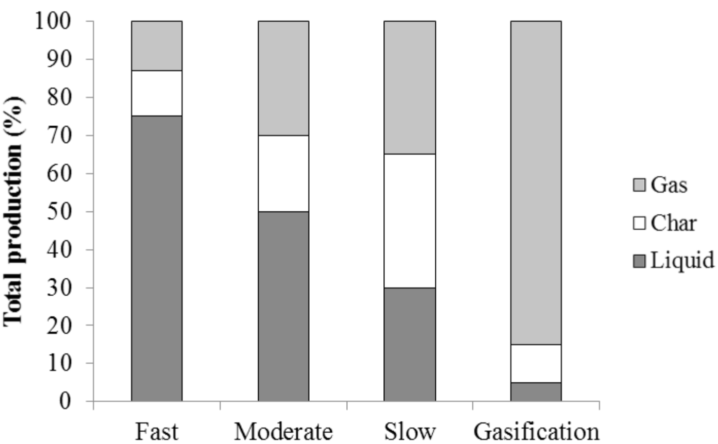

Fig. 1. Typical product yield (dry wood basis) obtained from different modes of pyrolysis of wood.
Fig. 1. Rendimiento típicos de productos (base madera seca) obtenida desde diferentes modos de pirolisis de madera.
Adapted from IEA, 2007.

Effects of biochar application into soils

Biochar production is often assessed through changes in the elemental concentrations of C, H, O and N and associated ratios. The ratios H/C and O/C are used to measure the degree of aromaticity and maturation, where these ratios tend to be higher in low-temperature biochars, partially charred plant materials and biochars produced during very short heating intervals (Krull et al., 2009). Original plant material and carbonization temperature determined are relevant in the proportions of atomic ratios (H/C, O/C, H/O, and C/N). However, temperatures above 500°C tend to remove characteristic of functional groups from the original material. Biochar structure is predominantly aromatic and heterogeneous, mainly consisting of condensed macromolecules. It is also chemically and biologically more stable than its original C sources, being characterized by high porosity (macro and microporosity) and a large surface area (Downie et al., 2009; Rodríguez, 2010). Based on this, biochar could produce diverse changes in soil properties that are necessary to consider.

Soil pH. Applications of biochar generally increase pH of soils and this contributes to the improvement of productivity of some crop systems (Gul et al., 2015; Case et al., 2015). In general, biochar has neutral to alkaline pH (8-10) and this allows neutralizing the soil pH in acid tropical soils (Wan et al., 2014). The alkaline pH of biochar is linked to the temperature of pyrolysis and the presence of carbonates in the raw material; the biochar from wood presents higher pH than other materials (Cornelissen et al., 2013; Cayuela et al., 2014; Gul et al., 2015). Increases in pyrolysis temperature result in increased biochar pH due to ash enrichment (Wan et al., 2014). However, the effect of the amendment on soil pH tends to decrease with time (Jones et al., 2012; Cayuela et al., 2014), due to probable oxidation, solubilization and/or absorption of functional groups caused by soil microbial activity or loss of alkaline metals (Cheng et al., 2006; Cheng et al., 2008; Jones et al., 2012; Cayuela et al., 2014). In acid soils, van Zwieten et al. (2010) reported an increase in pH from 4.2 to 5.9 in a Ferrasol with applications of biochar (10 t ha^{-1}).

Cation exchange capacity (CEC). In the soil, fresh biochar is oxidized by biotic and abiotic processes, increasing the negative charge on its surface and favoring the nutrient retention capacity of soil (Cheng et al., 2006). Cornelissen et al. (2013) demonstrated that pH and CEC increased (30-100%) in acid soils amended with biochar from maize and wood. Cheng et al. (2006) indicated that abiotic factors, such as incubation temperature, are more relevant than biotic factors (microbial activity) for producing hydrolysis and oxidation of biochar surface; they reported an increase in the cation exchange capacity (CEC) by 53% and 538% due to the formation of carboxylic functional groups, while oxygen content also increased by 4% and 38% after a few months of incubation at 30°C and 70°C, respectively. This indicates that oxidation of biochar at short-term allows the stabilization of this material, showing important effects on soil fertility and biogeochemistry. Lehmann et al. (2009) indicated that a significant portion of biochar interacts with the mineral surface found in the organo-mineral fraction. In addition, Nguyen et al. (2008) found an interaction of biochar with Al, Si, polysaccharides, and to a lesser extent with Fe, on its particle surfaces within the first few years after their application to the soil.

Greenhouse gas (GHG) emissions. Changes in climatic patterns cause a strong impact on the life cycle and ecosystems, and vice versa. In this sense, global stocks of SOC acquire relevance because of their importance in the global carbon (C) cycle and potential feedbacks to climate change (Reay et al., 2007; IPCC, 2014). The contribution of agricultural soils to carbon dioxide (CO_2), nitrous oxide (N_2O) and methane (CH_4) emissions depends on biophysical processes, soil management and incorporation/decomposition of organic residues in the soil (Reay et al., 2007; Muñoz et al., 2010; 2011a; 2011b). Lehmann et al. (2006) determined that up to 12% of the total anthropogenic C emissions by land use change evaluated in 0.21 Petagrams (10^{15} g; Pg) can be off-set annually in soil if the practice of slash-and-burn is replaced by slash-and-char. They also indicated that the implementation of a slash-and-char system is viable when most farmers are already familiar with charcoal production. Mitigation strategies focus on reducing net GHG emissions through adequate soil management. Table 1 shows the effect of biochar application on GHG emissions as reported in several studies. As there are contradictory results, more research on biochar application in different soils are required, also considering its use combined with other organic materials in order to elucidate the real effect of biochar on GHG emissions.

Soil biological activity. Reports show that there is a short-term decay of biochar up to 1.2% (60 days of incubation at 20°C mixed with sand) of initial biochar-C (Hamer et al., 2004), mainly due to the rapid degradation of aliphatic compounds that remain in the biochar (Cheng et al., 2006). However, biochar could affect other pro-

Table 1. Differences in greenhouse gas emission (CO_2, N_2O and CH_4) in soils amended with biochar.
Tabla 1. Diferencias en la emisión de gases de efecto invernadero (CO_2, N_2O and CH_4) en suelos enmendados con biocarbón.

Raw material of biochar	Pyrolysis temperature (°C)	Condition	Doses	Effect	References
Wheat straw	350-550	Field (rice crop)	20 t ha^{-1}	D' N_2O: 45.1 % I' CH_4: 30.6%	Zhang et al., 2013
			40 t ha^{-1}	D' N_2O: 39.5%	
		Field (rice crop)	20 t ha^{-1} 40 t ha^{-1}	D' N_2O: 37,6 D' N_2O: 41.2%	
Hardwood sawdust	550	Laboratory	10% w/w	D' N_2O: 63%	Thomazini et al., 2015
Thinnings of hardwood trees	180 – 440	Laboratory (biochar with mineral fertilizers)	28 t ha^{-1}	D' N_2O: 91%	Case et al., 2015
Pig manure	600	Laboratory (biochar with pig manure)	18 t ha^{-1} 18 t ha^{-1}	I' N_2O, 79% I' CO_2: 31% No effect in CH_4	Troy et al., 2013
		Laboratory (biochar without pig manure)		No effect in N_2O I' CO_2: 87% No effect in CH_4	
Different raw materials (16 types)	410 - 850	Laboratory	10% w/w	Variable results in GHG	Spokas and Reicosky, 2009
Pine chip	550	Field (anual ryegrasses)	5.7-18.8 t ha^{-1}	No effect on GHG	Angst et al., 2014
Wheat straw	350 – 550	Field (rice crop)	40 t ha^{-1}	I' CH_4: 34% D' N_20: 40 - 51%	Zhang et al., 2010
Different raw materials	400 – 500	Field/Laboratory (Meta-analysis of 30 researches)	1-2; 2-5; 5-10% w/w	D' N_2O: 54%	Cayuela et al., 2014; 2015
		Field/Laboratory (Meta-analysis of 56 researches)		D' N_2O: 49%	

I': Increase; D': Decrease; GHG: greenhouse gas

cesses in the soil, producing a decomposition of labile C compounds, as indicated in the study conducted by Hamer et al. (2004). In addition, aged biochar may behave differently from fresh biochar, and the interaction with labile organic compounds and mineral particles may also change the behavior of biochar in soils. There is need for more long-term decay of biochar studies in order to increase our knowledge on soil-biochar interactions.

Thies and Rillig (2009) showed that porous structures of biochar are likely to provide a highly suitable habitat for microbes to colonize, grow and reproduce. In fact, biochar pores act as a refuge site or microhabitat particularly for bacteria, actinomycetes and arbuscular mycorrhizal fungi. These authors indicated that the high porosity of biochar may also allow retaining more moisture, also increasing water-holding capacity of soils and 'habitability' of biochar. Therefore, biochar produces an increase in the number of microbial communities and its activity, proportioning air, water and nutrients movement (Lehmann et al., 2011; Gul et al., 2015). However, this effect could not be observed at short term. Quilliam et al. (2013) reported that after three years the microorganisms are not able of colonize the biochar porosity. Quilliam et al. (2012) observed a decrease in the growth of some soil fungi, but a better colonization of arbuscular mycorrhizal in beans roots. However, Warnock et al. (2010) reported a decrease of the presence of these fungi in different soils amended with biochar, which indicates that phenols and polyphenols could inhibit mycorrhizal growth (Cheng et al., 2008; Warnock et al., 2010). Similarly, biological nitrogen fixation (BNF) is also affected by biochar applications. Rondon et al. (2006) reported an increase of BNF in beans (*Phaseolus vulgaris*) due to a higher availability of nutrients and higher pH. In addition, Mia et al. (2014) indicated that rates of 10 t ha^{-1} of biochar applications produce higher rates of BFN of red clover (*Trifolium pratense*).

Physical soil properties. Biochar applied as an organic soil amendment contributes to the modifications of physical soil properties such as texture, structure, porosity and bulk density, which consequently increase in water retention capacity (Verheijen et al., 2010; Jien and Wang, 2013; Peake et al., 2014; Nelissen et al., 2015). Some of the changes produced with the use of biochar in different soils are shown in Table 2. Different studies have reported a direct influence between the application of biochar and decreased bulk density, increased aeration capacity and improved soil structure (Laird et al., 2010; Jien and Wang, 2013; Peake et al., 2014; Liang et al., 2014; Mukherjee et al., 2014; Nelissen et al., 2015). Additionally, a direct relationship between the rate of biochar application and its effect on bulk density was observed by Peake et al. (2014), who reported lower bulk density at higher rates of application.

Herath et al. (2013) compared the effect of biochar on soil physical properties in an Andisol and an Alfisol in New Zealand, and determined that biochar addition increased macroporosity and mesoporosity in the Alfisol and Andisol, respectively, as well as other soil physical properties, suggesting that biochar application may facilitate drainage in poorly drained Alfisol soils. Few studies are found in the literature that investigate degraded soils of volcanic origin and the effect of biochar additions on soil properties and/or their influence on C sequestration and global warming.

Local experiences. In Chile, few studies on biochar application in soils have been conducted. Altamirano et al. (2013) used biochar from *Pinus radiate* on a maize crop in an Andisol (5 t ha^{-1}), determining improvements in soil quality, crop growth and early cob maturation. Curaqueo et al. (2014) applied different doses of biochar (0, 5, 10 and 20 Mg ha^{-1}) in an Inceptisol and an Andisol, and determined improvements in the physical and chemical properties of the soils and an increase in barley yield (with higher doses).

There is a need to increase knowledge at both local and international levels. Economic and technical aspects need to be included, also considering that many studies have provided a basic understanding of the potential for biochar application in soils as well as the primary implications for biochar management that could contribute to create a comprehensive plan and/or development for a continuous use of biochar in (i) soil improvement, (ii) climate change mitigation, (iii) renewable energy and (iv) waste management.

CONCLUSIONS

The restoration of degraded soils is a key issue to increase soil productivity, to reduce the poverty of the rural community and minimize the environmental damage to the natural resources. A promissory alternative is the use of stabilized C as biochar from industrial or agricultural wastes, which has beneficial effects on the physical and chemical properties of the soil and consequently results in improved soil quality. The use of biochar as a soil amendment is also considered an appropriate tool for C sequestration, and an alternative to improve some soil properties (such as pH in acidic soils, cation exchange capacity and porosity), producing a decrease in bulk density, while it can also act as a microhabitat to soil microorganisms.

The number of studies on biochar management has increased in the last few years, but there is still little information on the effect of biochar in volcanic soils, considering their particular properties of C stabilization and nutrient cycling. Based on this, the authors consider that there is a gap of knowledge on the potential use of biochar in volcanic soils and its implications in GHG emission, since the results described in the literature and analyzed in this review show no consensus regarding the implications in the processes of gas emissions.

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Table 2. Changes in soil physical properties with biochar applications under different pyrolysis conditions and raw materials.

Tabla 2. Cambios en las propiedades físicas del suelo con aplicaciones de biocarbón bajo diferentes condiciones de pirolisis y materias primas.

Raw material of biochar	Type/ temperature of pyrolysis	Trial condition	Application rate	Effects	References
Mixed hardwood	Slow pyrolysis	Laboratory	0, 5, 10, and 20 g biochar kg^{-1} soil	I' SSA: 130 to 153 m2 g^{-1} R' BD I' WHC	Laird et al., 2010
Hard and softwood	480°C	Field (2-years)	20 t ha^{-1} (on dry weight basis)	R' BD I' porosity I' soil aggregation	Nelissen et al., 2015
Corsican Pine woodmill waste (*Pinus nigra* Arnold)	Gasified at 1000°C and PY at 450°C	Laboratory (eight soil types)	4 t ha^{-1} 20 t ha^{-1} 100 t ha^{-1}	R' BD: 2.1% to 6.1% R' BD: 0.5% to 6.6% R' BD: 4.2% to 19.2%	Peake et al., 2014
Waste wood of white lead trees (*Leucaena leucocephala* Lam.)	700°C	Laboratory (eroded and acidic Ultisol)	0, 2.5 and 5% w/w	R' BD: 1.42 Mg m^{-3} to 1.08 Mg m^{-3} I' total porosity: > 50% I' erosion resistance	Jien and Wang, 2013
Mixture of rice husk and shell of cotton seed	400°C	Field (3-years, calcareous soil)	90 t ha^{-1}	R' BD: 1.4 to 1.31 g cm^{-3} I' WHC: 9%	Liang et al., 2014
Oak wood	650°C	Field	0.5% w/w	R' BD: 24%	Mukherjee et al., 2014
Ground pecan shells (*Carya illinoinensis* Wangenh)	700°C	Laboratory (Loamy sand soil)	0, 5,10 o 20 g kg^{-1} of soil	No effects on aggregation and infiltration rate	Busscher et al., 2010
Rice straw (*Oryza sativa* L.)	250-450°C	Laboratory (Ultisol)	Into 50 g soil at a rate of 1% by dry weight	R' aggregate stability : 1-17.1%	Peng et al., 2011
Corn stover (*Zea mays* L.)	350 and 550°C	Laboratory (Alfisol) Laboratory (Andisol)	17.3, 11.3 and 10.0 t ha^{-1}	I' aggregate stability: >17% I' aggregate stability: 7 to 15%	Herath et al., 2013
Commercial biochar	400°C	Field (silt loam soil)	9 t ha^{-1}	I' WHC: 11%	Karhu et al., 2011
Wheat straw	525–550°C	Laboratory (loamy sandy soil)	2 w%	I' WHC: 32%	Bruun, 2011
Herbaceous plant cuttings	400 and 600°C 400°C	Field (sandy soil)	10 t ha^{-1} 1, 5, 20 and 50 t ha^{-1}	No effects: WHC, aggregate stability and saturated hydraulic conductivity	Jeffery et al., 2015

I': Increase; R': Reduce; SSA: Specific surface area; BD: Bulk density; WHC: Water holding capacity.

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