Geoderma 269 (2016) 99–107

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

The effect of straw and wood gasification biochar on carbon sequestration, selected soil fertility indicators and functional groups in soil: An incubation study

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ARTICLE INFO

Article history:
Received 5 November 2015
Received in revised form 19 January 2016
Accepted 21 January 2016
Available online 6 February 2016

Keywords:
Gasification biochar
Aggregate stability
Clay dispersibility
Soil carbon sequestration
Fourier transform infrared spectroscopy
Cation exchange capacity

ABSTRACT

Annual removal of crop residues may lead to depletion of soil organic carbon and soil degradation. Gasification biochar (GB), the carbon-rich byproduct of gasification of biomass such as straw and wood chips, may be used for maintaining the soil organic carbon content and counteract soil degradation if applied to soil. This study investigated the effect of straw removal and GB addition on soil biological, chemical and physical properties in a 22-months soil incubation study with a temperate sandy loam soil.

Soil application of wood and straw GB (WGB and SGB) resulted in very low CO_2 emissions, confirming the stability of the material against microbial degradation. Both GBs increased total organic carbon, cation exchange capacity and pH of the soil. The application of SGB and WGB did not affect aggregate stability, whereas SGB did not affect and WGB decreased clay dispersibility. In contrast, the addition of straw resulted in a high soil respiration rate, and about 80% of the added carbon was respired at the end of the incubation. However, the addition of straw increased aggregate stability and decreased clay dispersibility. Results from Fourier transformed infrared photoacoustic spectroscopy revealed a lower content of O–H and aliphatic C–H together with a higher content of aromatic groups in soils amended with GB compared to soils amended with straw. This suggested that the improvement in aggregate stability in straw treatments could be related to microbial derived aliphatics and simple sugars, and that increased stability against microbial degradation in biochar amended soil was related to highly condensed aromatic groups. Addition of nutrients (N, P and S) together with straw resulted in higher soil respiration compared to the straw treatment, but did not cause differences in other soil processes.

Results from this study suggest that GB has a potential for increasing soil carbon sequestration, CEC and pH. However, the straw turnover process plays a vital role for aggregate stability and clay dispersibility. Thus, annual straw removal on loamy soil needs to be considered with care in order to avoid soil degradation and risk of soil compaction or erosion.

1. Introduction

There is an urgent requirement for efficient and sustainable renewable energy technologies that use the limited amount of biomass and waste materials available effectively while replacing non-renewable fossil fuels. Thermal gasification technologies have proved to be a highly efficient platform to utilize a series of biomass resources such as straw and wood chips in a process that is applicable on small or medium scale (Ahrenfeldt et al., 2013). Besides bioenergy, thermal gasification produces a residual material (a variable mixture of ash and char components), often termed gasification biochar, with properties potentially improving soil fertility (Hansen et al., 2015; Müller-Stöver et al., 2012) and crop productivity (Jeffery et al., 2011). Until now, most of the studies have been conducted with pyrolysis biochar that often demonstrates initial microbial degradation of its labile compounds (Bruun et al., 2012). In contrast, gasification biochar (GB) produced at high temperature (700–1000 °C) is rather recalcitrant towards microbial degradation and has a lower content of surface functional groups compared to pyrolysis biochar, produced at lower temperatures (Brewer et al., 2011).

Currently, agricultural residues such as straw are often directly soil-incorporated, a strategy widely used among farmers to manage crop residues and to increase the content of soil organic carbon (SOC) (Villamil et al., 2015). Soil carbon sequestration contributes to climate change mitigation, and a high level of SOC is one of the most important soil-quality parameters (Lal, 2009). It is therefore a concern that straw

Abbreviation: GB, Gasification biochar; SGB, Straw gasification biochar; WGB, Wood gasification biochar; DOC, Dissolved organic carbon; SMB-C, Soil microbial biomass-carbon; N_{min}, Mineral nitrogen; TOC, Total organic carbon; CEC, Cation exchange capacity.

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http://dx.doi.org/10.1016/j.geoderma.2016.01.033
0016-7061/

removal for bioenergy production may decrease the SOC pool and soil quality (Blanco-Canqui, 2012). However, as the straw degrades rapidly by microorganisms, a major part of the straw-carbon returns to the atmosphere rather quickly as a result of microbial respiration (Powlson et al., 2011). Furthermore, carbon sequestration from incorporated residues in agricultural soils has been reported to be much lower than expected which may be due to the lack of available mineral nutrients needed for soil organic matter formation. Kirkby et al. (2013) found that stable soil organic matter has a constant ratio of carbon to nitrogen to organic phosphorus to sulfur (C:N:OP:S), and the authors found evidence that availability of those nutrients to the soil microbial biomass is essential for carbon sequestration from C-rich residues incorporated in arable soil (Kirkby et al., 2014).

Straw carbon converted to biochar in a gasification process has an aromatic structure less prone to microbial degradation and therefore a higher potential for carbon sequestration compared to the original feedstock when amended to soil (Brewer et al., 2011; Hansen et al., 2015). In addition, biochar originating from forest residues (unified as wood chips) could be regarded as a promising supply chain for transferring forest carbon to the agricultural cropping system addressing the problem of degrading soil quality (Lehmann et al., 2006). However, the benefits of soil organic matter for soil fertility result actually to a great extent from its microbial turnover (Janzen, 2006). Microbial degradation of organic matter releases organic compounds that act as binding agents for soil minerals into aggregates (Elmholt et al., 2008) and the generated aggregate stability is vital for the soils' ability to resist disintegration during tillage and increases resistance to erosion and crusting (Le Bissonnais, 1996). Elmholt et al. (2008) suggested that low input of organic matter results in increased risk of clay dispersion which can contribute to formation of cemented crusts on the soil surface. The application of straw has been shown to improve soil aggregate stability (Karami et al., 2012) and together with manure application also decreased clay dispersibility (Abdollahi et al., 2014). Soil organic matter also contributes to cation exchange capacity (CEC) of soil, which is vital for nutrient retention. Replacing straw inputs with a biochar amendment therefore raises the question of how the soil fertility parameters such as aggregate stability, clay dispersibility or cation exchange capacity will be affected. The information on the ability of biochar to act as a binding agent or be entrapped in soil aggregates as well as its overall effect on aggregate stability and clay dispersibility is contrasting. Biochar application has been shown to increase soil aggregate stability due to internal cohesion through the binding of mineral particles and carbon (Soinne et al., 2014; Sun and Lu, 2014). Khademalrasoul et al. (2014) reported increasing aggregate stability with increasing biochar rates, but also increased clay dispersibility, probably due to the high pH and low electrical conductivity.

The overall aim of this study was to compare the effect of soil amendment with either GB or straw on carbon sequestration and soil physical, chemical and biological properties in a 22 months soil incubation study. Our hypotheses were: (1) GB is stable towards microbial degradation and has therefore a higher potential for soil carbon sequestration compared to straw; (2) Carbon sequestration with straw can be increased by adding specific nutrients in the right ratio according to Kirkby et al. (2014); (3) Soil application of straw leads to higher microbial activity compared to GB and thereby results in larger improvements in soil physical and chemical parameters.

2. Materials and methods

2.1. Biochar, straw and soil

Two GBs were used in this study: straw gasification biochar (SGB) produced in a Low Temperature Circulating Fluidized Bed Gasifier (LT-CFB) at 700–750 °C and wood gasification biochar (WGB) produced in a TwoStage Gasifier at 1000–1200 °C (Ahrenfeldt et al., 2013). The straw used for SGB production originated from winter wheat (*Triticum aestivum* L.) cultivated in Zealand, Denmark. Commercially produced wheat straw pellets were crushed prior to LT-CFB gasification. Commercially produced pine wood chips (*Pinus spp.*) originating from Zealand, Denmark, were used for the production of wood gasification biochar (WGB). Biochar characterization is shown in Tables 1 and 2. More details about the production process and further characteristics of both SGB and WGB can be found in Hansen et al. (2015). The straw used for the incubation originated from winter wheat (*Triticum aestivum* L.) and was ground to a particle size of ≤5 mm prior to the incubation. A sandy loam soil from a conventional agricultural field on Bregentved estate, Zealand, Denmark (55° 22′ N, 12° 05′ E) was collected from the plow layer (0–25 cm), air dried and sieved to obtain a fraction ≤6 mm. The total soil C content was 1.52% and total N 0.18%. The soil contained 14% clay (<0.002 mm), 14% silt (0.002–0.02 mm), 47% fine sand (0.02–0.2) and 24% coarse sand (0.2–2 mm) and the pH was 7.9 (water).

2.2. Design of the incubation study

The incubation experiment included 5 treatments with 3 replicates each: (1) Control soil (C), (2) soil amended with 5% (*w*/w) straw (S), (3) soil amended with 5% (*w*/w) straw + supplementary nutrients (SN), (4) soil amended with 5% (*w*/w) straw gasification biochar (SGB) and (5) soil amended with 5% (*w*/w) wood gasification biochar (WGB). The relatively high rate of 5%, corresponding to about 100 t ha^{-1}, was chosen to simulate the effect of several years of biochar amendment, but also the heterogenic application in the field, which may create spots with very high concentrations. The straw, SGB and WGB, 400 g each, were thoroughly mixed with 8 kg dry soil, respectively, and filled into plastic containers with drainage holes in the bottom. A nutrient solution containing 0.32 g N, 0.07 g P and 0.07 g S kg $soil^{-1}$ (as $NH_4NO_3^-$, KH_2PO_4 and $MgSO_4 \times 7H_2O$, respectively) was added to each container of the SN treatment. These nutrient concentrations were calculated using a C:N:P:S ratio of 10,000:918:180:141. The rates of added nutrients were calculated to achieve 30% humification of the freshly added straw-C (Kirkby, personal communication). For measurement of soil respiration (see below), a plastic pipe (12 cm high and 10 cm in diameter), was placed in the middle of each container and pressed down to a depth of 9 cm and left permanently. The water content of the soil mixtures was adjusted to 50% of the respective water holding capacity (WHC) (determined separately for each mixture), and kept constant by watering up to weight every third week, which resulted in a maximum water loss of 5%. Containers were incubated uncovered at a constant temperature of 22 °C in the dark for 22 months (645 days).

2.3. Soil analyses and soil respiration

Soil samples of approximately 70 g, one per each replicate, were taken 8 times during the experiment (at day 1, 37, 72, 143, 228, 388, 494 and 645) with a 2 cm soil auger. The holes were filled with sand after each sampling. The soil was analyzed for total organic carbon (TOC), total organic nitrogen (TON), mineral nitrogen (N_{min}), soil microbial biomass-carbon (SMB-C), dissolved organic carbon (DOC) and soil pH. For TOC analyses, 50 mg of dry and ball-milled soil was weighed into tin capsules. The TOC and TON were measured on an elemental analyzer (Elementar Analysensysteme GmbH, Hanau, Germany). For N_{min}, SMB-C and DOC analyses, 10 g of fresh soil was extracted with 50 mL 0.5 M K_2SO_4. The suspensions were shaken on a horizontal shaker for 1 h (2.5 Hz), filtered through pleated filter paper (Grade 202F, Frisenette Aps, Denmark) and stored at −20 °C until analysis. The extracts were analyzed for concentrations of NO_3^- and NH_4^+ on an AutoAnalyzer 3 (AA3 Bran and Luebbe, Norderstedt, Germany), and for DOC on a TOC-VCPH analyzer (Shimadzu Corp., Kyoto, Japan). The SMB-C content in each treatment was determined by fumigation of an additional 10 g