Catena 135 (2015) 313–320

Contents lists available at ScienceDirect

Catena

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

Effects of biochar application rate on sandy desert soil properties and sorghum growth

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ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form 17 August 2015
Accepted 20 August 2015
Available online 3 September 2015

Keywords:
Sandy desert soils
Fast pyrolysis
Hydraulic properties
Plant growth
Soil fertility

ABSTRACT

The addition of biochar (BC) has been suggested to increase the soil fertility and crop productivity of agricultural lands. This study evaluated the effect of different levels of BC on properties of sandy desert soils and its ultimate impact on plant growth. The samples of desert sand were taken from the Kubuqi of Inner Mongolia, China and the Thar Desert, Pakistan. The sands were treated with a BC made from the fast pyrolysis of pine sawdust at 400 °C. Four BC application rates i.e. 0, 15, 22 and 45 t ha^{-1} were used in this study. Effects of BC addition on the water consumption and plant growth of sorghum were monitored for eight weeks in a pot experiment. The hydraulic and chemical properties of soil were analyzed to discern the effect of BC on the fertility of sandy desert soils. The results showed that BC amendment significantly improved soil hydraulic and chemical properties. The BC applied at the rate of 22 t ha^{-1} provided the best results as compared to all other treatments. Compared with the control group, the soil water-holding capacity (WHC) increased by 11% and 14%, water-retention capacity (WRC) increased by 28% and 32% and hydraulic conductivity decreased by 32% and 7% under the Kubuqi and the Thar Desert soils, respectively when BC was applied at 22 t ha^{-1}. Similarly, total C increased by 11% and 7%, total K increased by 37% and 42%, total P increased by 70% and 68% and total Ca increased by 69% and 75% while soil pH significantly reduced by 0.67 and 0.79 units, in the Kubuqi and the Thar Desert soils, respectively. The sorghum dry matter yield (DMY) was also significantly improved by 18% and 22% under the Kubuqi and the Thar Desert soils, respectively. The higher sorghum DMY consequently improved water-use efficiency (WUE) by 40% and 41% under the Kubuqi and the Thar Desert soils, respectively. In contrast, the plant growth and DMY declined at higher application rate (45 t ha^{-1}) of BC. The BC made from fast pyrolysis of pine sawdust at a temperature of 400 °C showed great potential in improving the quality of sandy desert soils. Hence, it can be used for sandy desert soil management.

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1. Introduction

The world's population is expected to increase by 65% up to year 2050. The additional food required to feed future generations will put further pressure on soil and water resources (Yu et al., 2013). At present, about 22% of world's total population lives in China and it will continue to increase with the same magnitude. It is anticipated that China will be facing the challenges of food shortages in the years to come (Peng et al., 2011). To meet food requirements of ever increasing population in China and elsewhere, additional soil resources need to be exploited and utilized. Dry lands contribute about 47.2% of the world's total land area (Lal, 2004). Most soils in dry regions are considered marginal for agriculture due to coarse-texture (Sun et al., 1998), low water and nutrient retention capacity (van Asperen et al., 2013) and low in soil organic C (Lal, 2004). For sustainable soil quality, the aggregate structure of soil plays an important role and the addition of organic C can improve soil aggregation and its physical and chemical properties (Fallahzade and Hajabbasi, 2012). Sandy deserts cover a significant portion of land and occur all over the world. China is no exception and occupies about 7% of the world's total arable land. If the soil quality of Chinese sandy deserts was improved, then this would be useful for desert restoration throughout the world. Desert lands in China could be used as an additional source for cultivation in order to enhance food production to meet future needs of increasing population (Fallahzade and Hajabbasi, 2012).

BC is a C rich organic material which is produced by thermal decomposition of plant-derived biomass in partial or total absence of oxygen (Sohi et al., 2010). The stability of BC in soil environment has been reported up to 1000 years (Sohi et al., 2010). Recently, BC has been used in arable soils for improving soil physical properties and plant growth (Liu et al., 2014; Lu et al., 2014). The use of BC in sandy soils increases soil organic C (Busscher et al., 2010), water-holding capacity (Kinney et al., 2012), and nutrient retention (Shafie et al., 2012) and improves

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http://dx.doi.org/10.1016/j.catena.2015.08.013
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aggregate stability and water content at permanent wilting point (Abel et al., 2013). It has been reported that BC amendment in sandy soil increased maize yield up to 150% (Uzoma et al., 2011b), radish yield by 96% (Chan et al., 2008), cherry tomato yield by 64% (Hossain et al., 2010) and also improved tomato yield by 13% under deficit irrigation (Akhtar et al., 2014). BC has been mostly applied in conventional arable soils (Laird et al., 2010; Major et al., 2012; Peng et al., 2011); few studies have focused on the use of BC in dry lands (Laghari et al., 2015; Mulcahy et al., 2013; Uzoma et al., 2011a; van Asperen et al., 2013). To our knowledge, there is little information on the effect of BC on plant growth and soil response in sandy desert soils.

This study was undertaken with three specific objectives: (i) to evaluate physicochemical properties of BC derived from the fast pyrolysis of pine sawdust, (ii) to quantify the impact of BC amendment on plant growth and dry matter yield (DMY) of sorghum in sandy desert soils collected from the Kubuqi and the Thar Desert, and (iii) to determine the effects of BC amendment on hydraulic characteristics and chemical properties of both sandy desert soils. We hypothesize that (i) the BC made from fast pyrolysis of pine sawdust at low reactor temperature (400 °C) will be acidic when used as a soil amendment, so it will decrease soil pH, increase total soil C and plant nutrient content, (ii) amending sandy desert soils with fast pyrolysis BC will improve soil hydraulic properties, and (iii) appropriate application rate of the BC will enhance plant growth and improve water-use efficiency in sandy desert soils.

2. Materials and methods

2.1. Biomass feedstock

The pine sawdust was collected from a furniture factory of Huazhong University of Science and Technology (HUST), Wuhan, China. The particle size distribution by mass of the pine sawdust was as follows: 55% below 1.5 mm, 36% from 1.5 to 1.8 mm, 7% from 1.8 to 2.5 mm, and 2% from 2.5 to 3.0 mm. The proximate and ultimate analyses of the feedstock are shown in Table 1.

Table 1
Physicochemical properties of feedstock and produced biochar.

Elements	Pine sawdust	Biochar
Yield (%)	–	51.0
pH	–	4.2
EC (dS m^{-1})	–	0.5
CEC ($cmol_+$ kg^{-1})	–	21.5
Proximate analysis (%)		
MC	4.5	3.5
VM	82.0	29.2
Ash	1.3	3.2
Fixed carbon	12.1	64.1
Ultimate analysis (%)		
C	36.2	51.7
N	0.19	0.86
C/N ratio	222.7	70.0
Plant nutrients (g kg^{-1})		
Ca	–	270.4
P	–	17.8
K	–	78.1
S	–	31.0
Al	–	19.0
BET (m^2 g^{-1})	–	6.2
Pore volume (m^3 g^{-1})	–	0.011
Average pore size (nm)	–	53.2
WHC (g g^{-1})	–	4.0

EC, electrical conductivity; CEC, cation exchange capacity; MC, moisture content; VM, volatile matter, BET, Brunauer–Emmett–Teller surface area; WHC, water-holding capacity; ND, not detected.

2.2. BC preparation

The BC was made using a lab-scale screw-type continuous-feed fast pyrolysis reactor (Fig. 1) at Bioenergy Laboratory, School of Environmental Science and Engineering, HUST, China. The setup comprised a stainless steel tube reactor (ID 81 mm, OD 89 mm, and height 114 mm) that was externally heated with an electric furnace. The temperature of the reactor was controlled homogeneously by a thermocouple with an accuracy of ± 5 °C. Pyrolytic runs were performed to produce BC at 400 °C under limited O_2 condition in triplicate. For BC production, the reactor was first allowed to heat up to the desired pyrolysis temperature, then the feedstock was loaded into the hopper, and the feed screw motors were switched on at 30 rpm at the feed rate of 0.18 kg h^{-1}, while the biomass particle pyrolysis time was kept constant at 3 s. After pyrolysis, the reactor was switched off and allowed to cool to ambient temperature. The BC was collected from the ash bucket, weighed, and stored in airtight containers for characterization and further experimentation.

2.3. BC characterization

The BC yield was calculated on wet basis. For chemical analyses, oven-dried BC samples were grounded in a ceramic pot and sieved through a 0.15-mm sieve. Chemical analyses were conducted in triplicate. The proximate analysis was conducted following ASTM D 3176 (ASTM, 2006). The elemental compositions of BC such as C, H, N, S and O were determined by the dry combustion method using a CHNS/O analyzer (Vario Micro Cube; Elementar, Germany). Total oxides of different elements such as Mg, Al, P, K, and Ca in the BC were determined by X-ray fluorescence (EDAX, Mahwah, NJ, USA). The pH and electrical conductivity (EC) were measured in 1:10 (w v^{-1}) BC to deionized water after shaking the samples on a mechanical shaker at 200 RPM for 1 h. A PHS-3C digital glass electrode precision pH meter and a DDS-307 digital glass electrode conductivity meter (Analytical Instruments Co., Ltd., Shanghai, China) were used to test the pH and EC, respectively. The cation exchange capacity (CEC) of the BC was measured using the 1 M ammonium acetate (pH 7) method described by Wu et al. (2012). Details have been provided in the Supplementary information (SI). The Brunauer–Emmett–Teller (BET) surface area of the BC was determined using an accelerated surface area porosimetry system (ASAP2010; Micrometrics, Norcross, GA, USA). The X-ray diffraction (XRD; X'Pert PRO; PANalytical B.V., Almelo, Netherlands) analysis was carried out to identify the crystallographic structure of the BC. The Fourier transformation infrared (FTIR) analyses of the BC were carried out using a VERTEX 70 FTIR Spectrometer (Bruker, Ettlingen, Germany). The BC samples were scanned at the mid-infrared electromagnetic spectrum range of 4000 to 400 cm^{-1} wave numbers. To analyze the surface morphology of the BC, scanning electron microscope (SEM) (EMINI 1530; Oberkochen, Germany) imaging analyses of the BC samples were conducted. The WHC of the BC was measured gravimetrically according to the procedures described by Kinney et al. (2012) with slight modification. Simply, we soaked a 10-g oven-dried BC sample without further size reduction in distilled water in a glass beaker at 40 °C. After 1 h, we transferred the suspension in a clamped ceramic Buchner funnel wrinkled with cellulose filter paper (Whatman No. 1). The sample was allowed to drain freely for 1 h, and WHC was calculated as mass of water retained by the mass of dry BC while water absorbed by the filter paper was adjusted. The physicochemical properties of the BC are given in Table 1.

2.4. Soil sampling

Two different desert soils were used for experiments. First bulk samples were taken from an uncultivated area of Kubuqi desert (the 7th largest desert of China with an area of 16,600 km^2) located in southern section of Inner-Mongolia, China (39.588°N, 109.588°E). The second

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