Geoderma 331 (2018) 100–108

Contents lists available at ScienceDirect

Geoderma

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

Impact of biochar addition on soil properties and water-fertilizer productivity of tomato in semi-arid region of Inner Mongolia, China

Changjian Li[a], Yunwu Xiong[a,b,*], Zhongyi Qu[c], Xu Xu[a,b], Quanzhong Huang[a,b], Guanhua Huang[a,b]

[a] Center for Agricultural Water Research in China, College of Water Resources & Civil Engineering, China Agricultural University, Beijing 100083, PR China
[b] Chinese-Israeli International Center for Research and Training in Agriculture, China Agricultural University, Beijing 100083, PR China
[c] Water Conservancy and Civil Engineering College, Inner Mongolia Agricultural University, Hohhot 010018, PR China

ARTICLE INFO

Handling Editor: A.B. McBratney

Keywords:
Sandy loam
Solanum lycopersicum
Water use efficiency
Partial factor productivity

ABSTRACT

Biochar is proposed as a soil amendment to improve soil physical-chemical properties and crop productivity. However, the effect of biochar on crop yield is not consistent and the mechanisms affecting plant growth are still not well-understood. In this paper, field experiments were carried out to investigate the impact of biochar addition on soil properties, water and fertilizer productivity of tomato in semi-arid area of Inner Mongolia, China. The tested biochar was made from maize straw by slow pyrolysis. Four biochar treatments were conducted including addition of 10, 20, 40 and 60 $t\,ha^{-1}$ and no biochar as a control. Addition of biochar reduced the bulk density and increased the porosity of soil. Electrical conductivity of soil increased with increasing biochar application rate. Soil pH was not affected by addition of biochar in one growing season. Yield, crop water productivity and partial factor productivity for fertilizer were nonlinearly (quadratic) proportional to application rate of biochar. Highest water and fertilizer productivity obtained from the 40 $t\,ha^{-1}$ biochar treatment. Comprehensive analysis of biochar impact on yield, water and nutrient productivity, and cost-benefit for the grower indicate that addition of approximate 30 $t\,ha^{-1}$ is an appropriate rate for tomato production in the study area. This suggestion is based on the relatively short term effect and local market conditions. A prolonged experiment is desirable to understand the long term response of soil and crop to biochar addition.

1. Introduction

In arid and semi-arid regions of China such as mid-western region of Inner Mongolia, farmland degradation is serious and agro-ecosystems are vulnerable due to water shortage and poor soil organic matter content. In order to obtain high crop production, excess fertilizer is applied and a series of environmental problems occur such as nonpoint source pollution, soil degradation and desertification. The degradation and desertification of land may result in serious dust and sand storms (Gao et al., 2006). Diverse amendments are used to improve soil and water conditions, reduce risk of soil erosion and promote the productivity of agro-ecosystem (Larney and Angers, 2012). Biochar, characterized by large surface area, abundant micro-pores and high cation exchange capacity, is proposed as a means to sequester carbon and improve soil physio-chemical properties for crop growth (Beesley and Dickinson, 2011; Gaskin et al., 2008; Johannes et al., 2006).

Biochar is produced through pyrolysis of various feedstocks under high temperature and anaerobic conditions. The feedstocks can originate from a variety of biomasses including wood, crop residues, manure, composts, and sewage sludge. Biochar has large proportion of fused aromatic carbon giving a complicated pore structure and chemical stability (BřEndová et al., 2012; Lehmann et al., 2011). The physical and chemical properties of biochar, such as total surface area, pore size distribution and cation exchange capacity, differ as a consequence of several factors such as feedstock composition, pyrolysis temperature and duration (McBeath et al., 2014). Therefore, the influence of biochar on soil function is dependent on the type of biomass and pyrolysis procedures as well as application strategy (Ojeda et al., 2015; Streubel et al., 2011).

Tomato (*Solanum lycopersicum* Mill.) is one of the major cash crops in the arid and semi-arid region of Inner Mongolia due to the site-specific climate, sunlight, heat resources, and marketing opportunities. Tomato is a high water demanding crop requiring irrigation throughout the growing period since rainfall is much less than the evapotranspiration. Implementation of biochar addition to modify soil and water conditions (e.g., water and nutrient retention capacity, aggregate

Abbreviations: EC, Electrical conductivity; ET_0, evapotranspiration; DAT, Days after transplanting; DAI, Days after irrigation; ET_a, actual evapotranspiration; WP, Water productivity; PFP, Partial factor productivity; N, Nitrogen; P, Phosphorous; K, Potassium

* Corresponding author at: Center for Agricultural Water Research in China, College of Water Resources & Civil Engineering, China Agricultural University, Beijing 100083, PR China.
E-mail address: yxiong@cau.edu.cn (Y. Xiong).

https://doi.org/10.1016/j.geoderma.2018.06.014
Received 18 January 2018; Received in revised form 16 June 2018; Accepted 16 June 2018

stability) may improve yield and fruit quality and promote water and nutrient use efficiency of tomato (Akhtar et al., 2014).

Biochar incorporation into soil has an impact on soil pores, aggregate structure and hydrological functions such as water holding capacity and aggregate stability. Biochar application may influence soil through the following mechanisms: direct pore contribution, creation of accommodation pores between biochar and the surrounding soil aggregates, and improve persistence of soil pores due to increased aggregate stability (Hardie et al., 2014). Many studies have indicated that soil bulk density decreases while porosity and water retention capacity increase with addition of biochar (Abel et al., 2013; Baccile et al., 2009; Githinji, 2014; Herath et al., 2013; Karhu et al., 2011; Laird et al., 2010a; Oguntunde et al., 2008; Pereira et al., 2012; Yu et al., 2013). The degree of variation for bulk density and total porosity is dependent on type and particle size of biochar as well as application rate. In contrast, Jeffery et al. (2015) reported that biochar application does not improve the soil hydrological function of a sandy soil; and Hardie et al. (2014) found no significant difference in soil physical property between no biochar and biochar treatments, and that biochar application to a loamy sand soil has no significant effect on soil water availability. Ojeda et al. (2015) investigated the impact of biochar from different biomass sources (pine, poplar or sludge) and pyrolysis processes (slow, fast and gasification) on soil properties, and found that the influence on water retention is irrelevant for most of biochars. Haefele et al. (2011) found that bulk density in the top soil decreases significantly for clay and sandy clay soil, but not significantly for loamy sand soil after application of identical biochar. Therefore, the alteration of bulk density, porosity and hydraulic characteristics by biochar is not consistent and varies with soil type and biochar properties.

In addition to soil physical and hydraulic properties, application of biochar has the potential to alter soil pH (Glaser et al., 2002). Unger (2008) and Chintala et al. (2014) reported that biochar application slightly increases pH in acid soil, but decreases pH in alkaline soil. Column experiments showed that addition of 4% straw biochar (slow pyrolysis at 730 °C) to subsoil increased soil pH from 6.8 to 9.2, whereas addition the same amount of wood biochar (slow pyrolysis at 450–480 °C) did not affect the pH (Bruun et al., 2014). Laird et al. (2010a) found that biochar mixed with soil at the rate of 20 g kg^{-1} resulted in pH increasing by about 1 unit after 500 days of incubation for a loam soil.

Biochar has high electrical conductivity (EC) and contains a large number of base ions which may result in increased soil EC (Khan et al., 2016; Van Zwieten et al., 2010). Previous studies showed that soil EC increased differently for different soil types after biochar addition (Atkinson et al., 2010; Chintala et al., 2014; Curaqueo et al., 2014). Addition of corn straw and switch grass biochar to acidic soil increased EC according to the rate of application (Chintala et al., 2014). Hossain et al. (2010) found that addition of biochar made from wastewater sludge to chromosol soil increases EC by around 0.29 dS m^{-1}. However, Vidana Gamage et al. (2016) reported that addition of rice-husk biochar to sand and sandy loam soil did not significantly increase EC; and Tammeorg et al. (2014) found that EC was not significantly affected by biochar (produced by pyrolizing chips of debarked spruce and pine) application to a sandy clay loam soil.

Crop response to biochar application varies from negative to more than two-fold yield increase (Spokas et al., 2012). Meta-analysis has shown that biochar application results in an average increase by 10% crop productivity (Jeffery et al., 2011). For the cash crop of tomato, the influence in yield by biochar application is not consistent. Akhtar et al. (2014) found that biochar enhances yield and water productivity of tomato under deficit and partial root-zone drying irrigation. Hossain et al. (2010) reported that yield of tomato after application of 10 t ha^{-1} biochar (made by slow pyrolysis of wastewater sludge) was 64% higher than no biochar treatment. Petruccelli et al. (2015) reported that biochar made from different feedstocks (wheat straw, poplar, and olive residue) had different impacts on yield and nutritional quality of tomato. Warren (1971) reported that tomato yield is not different for biochar addition. Graber et al. (2010) found that biochar application had no effect on fruit yield but positively enhanced plant height and leaf size in soilless media. Water use efficiency is affected by addition of biochar as well. Batool et al. (2015) found that water use efficiency is improved under water stress condition by biochar application, and Kammann et al. (2011) found that there was a significant increase in water use efficiency by application of biochar in both sufficient and stressed water conditions.

Biochar application has the potential to improve soil fertility and nutrient retention thus promoting partial factor productivity for fertilizer. Biochar addition to soil may increase nutrient utilization either through nutrients contained in biochar or physical-chemical processes that allow better usage of soil-inherent or fertilizer-derived nutrients (Jeffery et al., 2011; Novak et al., 2009). For biochar to serve a beneficial role in revitalizing nutrient-deprived soils there should be a significant increase in the quantity of plant-available nutrients and its nutrition retention capacity (Sohi, 2013). Laird et al. (2010b) demonstrated that biochar significantly increased the retention of phosphorus and several other nutrients. Ding et al. (2016) showed that biochar addition could improve soil quality and reduce leaching of nutrients. Filed trial results have demonstrated a positive effect of biochar on availability of plant nutrients (Liu and Zhang, 2012). In contrast, other studies reported that nutrient availability can be very low with biochar application (Bridle and Pritchard, 2004).

Despite a large amount of research that has been conducted in the last few decades, the impact on crop (in particular tomato) of biochar usage is still inconsistent and unpredictable (Spokas et al., 2012). The mechanisms affecting plant growth, soil and environmental conditions resulting from biochar application are still not well-understood (Lehmann et al., 2015). The objectives of this research were: 1) to investigate the effects of biochar addition on the physical and chemical properties of a sandy loam soil; 2) to study the response of tomato growth and yield to biochar application at different levels; 3) to analyze the impact of biochar application on water and fertilizer productivity of tomato; and 4) to propose an appropriate biochar application strategy for tomato production in the study area.

2. Materials and methods

2.1. Experimental site description

Biochar application was conducted at the Water–Saving Irrigation Experimental Station of Inner Mongolia, China (40°16′N and 111°46′E, 1130 m above sea level) in 2013 and 2014. Climate in the study area is semi-arid temperate continental climate with mean annual precipitation of 392 mm and potential evaporation of 1850 mm. Precipitation shows a marked seasonality with approximate 70% rainfall occurring in the vegetation period from June to August. Mean annual temperature is 6–7 °C with the warmest month averaging 22.1 °C and the coldest month averaging −12.8 °C. The annual cumulative temperature above 10 °C is around 2700 °C. The mean annual day-length is around 2900 h. The frost-free period is approximate 120 days, and maximum frost depth is around 1.75 m.

Meteorological data, including maximum and minimum air temperature, relative humidity, rainfall, sunshine duration, wind speed and direction at 2 m above ground during the experimental periods, were measured by an automatic weather station (PESSL, T-warner, Germany). The daily reference evapotranspiration (ET_o) was calculated with modified Penman-Monteith equation according to FAO-56 (Allen et al., 1998) (Table S1).

Soil is classified as a Chestnut Cinnamon according to Chinese Soil Classification and Terminology. Texture analysis of superficial layer soil (0–30 cm) yields a sand content of 64.1%, a silt content of 16.5% and a clay content of 19.4%. Soil is classified as sandy loam according to the U.S. textural classification triangle. The mean bulk density is