Chemosphere 142 (2016) 176–183

Contents lists available at ScienceDirect

Chemosphere

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

Efficacies of designer biochars in improving biomass and nutrient uptake of winter wheat grown in a hard setting subsoil layer

G.C. Sigua [a,*], J.M. Novak [a], D.W. Watts [a], M.G. Johnson [b], K. Spokas [c]

[a] United States Department of Agriculture, Agricultural Research Service, Coastal Plains Soil, Water, and Plant Research Center, Florence, SC 29501, USA
[b] United States Environmental Protection Agency, National Health and Environmental Effects Research Laboratory, Western Ecology Division, 200 Southwest 35th Street, Corvallis, OR 97333, USA
[c] United States Department of Agriculture, Agricultural Research Service, St. Paul, MN, USA

HIGHLIGHTS

- Biochar was used to provide alternative recalcitrant carbon source in the soils.
- Additions of different designer biochars may have variable effects on biomass and nutrient uptake of winter wheat.
- Designer biochars did improve both aboveground and belowground biomass and uptake of winter wheat.

ARTICLE INFO

Article history:
Received 14 October 2014
Received in revised form 29 May 2015
Accepted 8 June 2015
Available online 22 June 2015

Keywords:
Designer biochars
Belowground biomass
Aboveground biomass
Hard setting subsoil

ABSTRACT

In the Coastal Plains region of the United States, the hard setting subsoil layer of Norfolk soils results in low water holding capacity and nutrient retention, which often limits root development. In this region, the Norfolk soils are under intensive crop production that further depletes nutrients and reduces organic carbon (C). Incorporation of pyrolyzed organic residues or "biochars" can provide an alternative recalcitrant C source. However, biochar quality and effect can be inconsistent and different biochars react differently in soils. We hypothesized that addition of different designer biochars will have variable effects on biomass and nutrient uptake of winter wheat. The objective of this study was to investigate the effects of designer biochars on biomass productivity and nutrient uptake of winter wheat (*Triticum aestivum* L.) in a Norfolk's hard setting subsoil layer. Biochars were added to Norfolk's hard setting subsoil layer at the rate of 40 Mg ha^{-1}. The different sources of biochars were: plant-based (pine chips, PC); animal-based (poultry litter, PL); 50:50 blend (50% PC:50% PL); 80:20 blend (80% PC:20% PL); and hardwood (HW). Aboveground and belowground biomass and nutrient uptake of winter wheat varied significantly ($p \leqslant 0.0001$) with the different designer biochar applications. The greatest increase in the belowground biomass of winter wheat over the control was from 80:20 blend of PC:PL (81%) followed by HW (76%), PC (59%) and 50:50 blend of PC:PL (9%). However, application of PL resulted in significant reduction of belowground biomass by about 82% when compared to the control plants. The average uptake of P, K, Ca, Mg, Na, Al, Fe, Cu and Zn in both the aboveground and belowground biomass of winter wheat varied remarkably with biochar treatments. Overall, our results showed promising significance for the treatment of a Norfolk's hard setting subsoil layer since designer biochars did improve both aboveground/belowground biomass and nutrient uptake of winter wheat.

Published by Elsevier Ltd.

1. Introduction

Norfolk soils in the southeastern U.S. Coastal Plain region have meager soil fertility characteristics because of their sandy textures, acidic pH values, kaolinitic clays and with depleted organic carbon contents. For more than 150 years, Norfolk soils of the southeastern U.S. have been cultivated for row crops, particularly winter wheat, corn and cotton (Novak et al., 2009a,b; Gray, 1933). Most of these agricultural soils are highly weathered Ultisols (Boul, 1973; Gardner, 1981). Extensive clay mineral weathering and clay eluviations along with intensive leaching of bases and high levels of exchangeable Al (Daniels et al., 1978; Gamble and Daniels,

* Corresponding author at: USDA-ARS-CPSWPRC, 2611 West Lucas St., Florence, SC 29501, USA.
E-mail address: gilbert.sigua@ars.usda.gov (G.C. Sigua).

http://dx.doi.org/10.1016/j.chemosphere.2015.06.015
0045-6535/Published by Elsevier Ltd.

1974) has promoted the formation of a hard setting subsoil layers (E horizon). These soil characteristics severely limit fertility and crop productivity, which leaves few management options for improvements (Novak et al., 2009a).

An additional issue with farming in the sandy Coastal Plain is the formation of a hard setting subsoil layer. In the Norfolk soil series, for example, the hard setting subsoil layer results in low water holding capacity that impedes root development. According to Mullins et al. (1990), hard setting soils are soils that are hard, structureless mass during drying and are thereafter difficult or impossible to cultivate until the profile is rewetted. There are at least three agronomic limitations of hard setting subsoil layer in the Norfolk soils: difficulty in producing a good tilth; constraints to seedling emergence; and constraints to root growth. It is generally accepted that compaction restricts root growth and crop production. Oussible et al. (1992) have shown that root penetration in deep soil layers was hampered by subsurface compaction. Excessive soil compaction impedes root growth and therefore limits the amount of soil explored by roots (Ahmad et al., 2009).

As a counter measure to these soil limitations, the Natural Resource Conservation Service and the Agricultural Research Service have developed soil and water conservation management practices (i.e., deep tillage, deep disruption, etc.) for these soils that promote productivity (Novak and Busscher, 2012). Unfortunately, the beneficial effects of tillage are temporary; deep disruption must be done annually (Busscher et al., 2000; Carter et al., 1996). It has been postulated that increasing the organic C content of the hard setting subsoil layer may promote soil aggregation and root penetration. The soil organic C levels are concentrated at the surface or deteriorate in the hot, wet weather (Wang et al., 2000; Parton et al., 1987). An ideal organic carbon-enriched amendment for these soils would be one that is long-lasting and increases aggregation, fertility and water retention (Novak and Busscher, 2012). Recently, Laird (2008) described how a long-lasting technology could be adopted as a management strategy to revitalize soils. In South America, pre Columbian Amazonian inhabitants improved their infertile soils by applying biochars (Lehmann et al., 2006; Glaser et al., 2002). Carbon in the form of biochar is resistant to degradation, having remained in tropical Amazonian soils for centuries (Steiner et al., 2007).

Biochars have been produced from a wide variety of organic materials including forestry and crop residues, paper mill sludge and poultry waste (Chan and Xu, 2009). The influence of biochar on soil properties and crop productivity is likely to vary significantly among biochars because biochar's effectiveness are governed by biomass sources and pyrolysis conditions (Chan et al., 2007, 2008; Gaskin et al., 2008; Chan and Xu, 2009; Nguyen et al., 2010). Accordingly, biochars quality can be variable and different biochars react differently in soils (Sigua et al., 2014; Novak and Busscher, 2012). Novak et al. (2009b) recognized that biochars could be designed with specific chemical and physical properties to target specific soil deficiencies. He perceived that a biochar could be designed to improve the tilth of a hard setting subsoil layer. Since one biochar type will not resolve all issues in all soils, there is a need to conduct additional research on the efficacy of designer biochars in improving biomass and nutrient uptake of crops grown in soils especially with hard setting subsoil layer. We hypothesized that the addition of different designer biochars to a hard setting subsoil layer will have variable effects on biomass and nutrient uptake of winter wheat. The objective of this study was to investigate the effects of multiple designer biochars on biomass and nutrient uptake of winter wheat (*Triticum aestivum* L.) grown in Norfolk soil with hard setting subsoil layer.

2. Materials and methods

2.1. Soil and site description

The Norfolk soil series (fine loamy, kaolinitic, thermic, Typic Kandiudult) was used in the study. This soil is classified as an Ultisols order (US Soil Taxonomy) that formed in extensively weathered Coastal Plain marine sediments with the clay fraction dominated by kaolinite. The Norfolk is a well drained soil located in upland landscapes (Daniels et al., 1978). This soil was collected from the Clemson University, Pee Dee Research and Education Center, Darlington, South Carolina. The collection site has a long history of row crop production (>30 yrs), which in 2007, was converted to switchgrass (*Panicum virgatum*) production.

The hard setting subsoil layer of the Norfolk was collected by removing the top 0–15 cm Ap horizon using a front-end loader. Using a shovel, soils were collected between 15 and 40 cm soil depths. The soil samples were air-dried; and then passed through a 2 mm sieve to remove plant material and large aggregates. Particle size analyses were carried out using the hydrometer method (Soil Characterization Laboratory, The Ohio State University, Columbus, Ohio). The organic carbon (SOC) and total nitrogen (TN) contents of Norfolk subsoil were measured using a LECO Truspec analyzer (LECO Corp., St. Joseph, Michigan). Table 1 summarized some selected soil physical and chemical properties of the soil used in the study.

2.2. Feedstock description, biochar production, and characterization

The three feedstocks were consisted of pine chips (PC), poultry litters (PL) and hardwoods (HW). The blending, pelletilization and pyrolysis procedures that were followed in this study were reported in the early paper of Sigua et al. (2014) and Novak et al. (2014). Biochars were produced from each of the pelletized feedstocks using a slow pyrolysis procedure at 350 °C (Cantrell and Martin, 2012). Each pelletized biochar particle had a length of between 10–20 mm and diameter of about 6–8 mm.

Hardwood biochar was also used in this study for comparison. The HW biochar was processed to <0.5 mm particle size to test if smaller size biochar was more effective at improving the hard setting subsoil layer. The HW biochar was manufactured from oak and

Table 1
Selected soil chemical and mineralogical properties of the soil used in the study.

Soil properties	Norfolk soil
1. Physical	
Sand (g kg^{-1})	807
Silt (g kg^{-1})	167
Clay (g kg^{-1})	26
Soil texture	Loamy sand
Bulk density (Mg m^{-3})	1.5
Porosity (%)	44
Penetration resistance (MPa)	1.1
2. Chemical	
pH	5.93
C (g kg^{-1})	5.81
N (g kg^{-1})	0.82
P (mg kg^{-1})	20.3
K (mg kg^{-1})	121.5
Ca (mg kg^{-1})	244.5
Mg (mg kg^{-1})	54.7
Na (mg kg^{-1})	29.6
Al (mg kg^{-1})	83.0
Fe (mg kg^{-1})	10.7
Cu (mg kg^{-1})	0.18
Zn (mg kg^{-1})	3.8