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Effect of biochar application method on nitrogen leaching and hydraulic conductivity in a silty clay soil

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ABSTRACT

Biochar is anticipated to be an effective option for mitigating nitrogen (N) leaching and improving the hydraulic characteristics of soil, particularly sandy soil. However, little attention has been paid to understanding the effect of biochar on N leaching and hydraulic conductivity (K) in fine-textured soil. Additionally, whether different biochar application methods have different effects on N leaching and K remains unclear. Therefore, our objective in this study is to determine the effects of biochar with different application methods on nitrate/ammonium leaching and K in silty clay soil. The three biochar application patterns were as follows: A, biochar was mixed into 0–10 cm of surface soil; B, biochar was mixed into 10–20 cm of subsurface soil; and C, biochar was mixed evenly into 0–20 cm of plow layer soil. In addition, biochar was added at three rates, namely, 1%, 2% and 4% (mass ratios), and a soil column without biochar addition served as the control (CK). Our results demonstrated that the choice of biochar application method significantly influenced N leaching and soil K and balance between the soil K and N leaching, particularly for nitrate. Additionally, the leaching of N in silty clay soil occurred mainly in nitrate form. Compared with the CK, all 1% biochar treatments increased nitrate leaching (except C1%, which showed no differences from the CK) and tended to decrease K. However, all 4% biochar treatments increased nitrate leaching due to a high K. All 2% biochar treatments significantly reduced nitrate leaching by 8.3–17.0%, and B2% significantly increased the saturated hydraulic conductivity (K_{sat}) of soil by 20.9%. Hence, the mixing of biochar at a rate of 2% into the subsurface soil effectively mitigated N leaching and increased K in silty clay soil. These findings could have some implications for the field application of biochar. For instance, the combination of subsurface biochar application with that of fertilizer to roots in orchards or with deep tillage in fields, which would mimic the B2% model, would yield multiple benefits, including lower costs.

1. Introduction

Water stress and nutrient deficits constitute the major constraints to primary production in arid and semiarid environments (Austin, 2011; Zand-Parsa et al., 2006). Nitrogen (N) fertilization is a common practice for achieving higher yields (Long et al., 2010; Malhi et al., 2012), but the performance of this practice still depends on the soil water status (Turner, 2004; Turner and Asseng, 2005; Zhong and Shangguan, 2014). Additionally, nitrate leaching is one of the main pathways through which N is lost from agricultural soils (Pratiwi et al., 2016), which results in not only a huge waste of resources but also serious environmental problems (Xu et al., 2016). Thus, technical solutions to mitigate N leaching and improve water status are needed.

Biochar, a solid, carbon-rich residue of biomass pyrolysis, has been proposed for carbon sequestration (Lehmann and Joseph, 2009; Woolf et al., 2010) and for improving soil productivity (Liu et al., 2016). Moreover, biochar has been heralded as a material that can prevent fertilizer leaching (Sun et al., 2015; Yoo et al., 2014) and increase both the hydraulic conductivity (K) and the water holding capacity of soil (Ajayi et al., 2016; Karhu et al., 2011; Obia et al., 2016).

The reduction in N leaching by biochar is most likely attributable to an increase in cation exchange capacity (CEC) and the physical retention of dissolved N (Sika and Hardie, 2014; Xu et al., 2016; Yoo et al., 2014). However, the effect of biochar on N leaching depends on the biochar application rate, the biochar type, the soil characteristics and the environmental conditions (Gao et al., 2016; Sorrenti and Toselli, 2016). Furthermore, biochar could affect the soil K (Barnes et al., 2014; Githinji, 2014; Masiello et al., 2015) and thus exert concomitant effects

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Table 1
Physical and chemical characteristicsof the biochar used in this study.

Specific surface area (m^2 g^{-1})	pH	CEC ($cmol\ kg^{-1}$)	Total C ($g\ kg^{-1}$)	Total N ($g\ kg^{-1}$)	NO_3^- ($mg\ kg^{-1}$)	NH_4^+ ($mg\ kg^{-1}$)	H ($g\ kg^{-1}$)	O ($g\ kg^{-1}$)
14.22	9.67	32.57	670.15	5.70	0.52	1.86	21.71	71.79
K	P	Na	Ca	Mg	Fe	Cu	Mn	Zn
6003.4	1802.1	639.2	24185.1	3196.5	5745.8	9.9	91.5	37.3

Note: The units of K, P, Na, Ca, Mg, Fe, Cu, Mn and Zn are $mg\ kg^{-1}$.

on the leaching of N, particularly in the form of soluble nitrate (Xu et al., 2016). Biochar may influence *K* by altering the soil porosity, pore shape, pore connectivity and tortuosity of the conducting soil pores (Castellini et al., 2015; Kameyama et al., 2012). The effect of biochar on *K* also varies with the type of biochar, soil texture and level of biochar use (Borchard et al., 2014; Mukherjee and Zimmerman, 2013). For example, Barnes et al. (2014) found that mesquite wood biochar amendment (10%; w/w) decreased the saturated hydraulic conductivity (K_{sat}) by 92% in sand and 67% in organic soil but increased the K_{sat} by 328% in clay-rich soil. Kameyama et al. (2012) reported that increases in the K_{sat} of clay soil were only obtained with higher-concentration bagasse biochar treatments (5–10%; w/w).

To date, little attention has been paid to the biochar-induced changes in both the nutrient leaching and *K* of fine-textured soil (Castellini et al., 2015), but previous studies have revealed that biochar appears to be effective for improving both the water status and the nutrient retention of sandy soils. For example, Novak et al. (2016) reported that pine chip biochar promoted water infiltration and increased water quality in a compacted subsoil layer of sandy soil. Haider et al. (2017) performed a four-year field experiment and found that wood chip biochar amendments significantly reduced nitrate leaching and improved the moisture content in sandy soil. Nevertheless, it is unclear whether biochar could both mitigate N leaching and increase *K* in fine-textured soil, and investigating this issue is essential for determining whether biochar can be used to improve soil quality in arid and semi-arid agriculture systems.

Furthermore, recent studies have reported that biochar application methods have significant effects on the hydraulic properties of soil due to the various structures in different soil layers and changes in soil porosity and continuity (Li et al., 2016; Liu et al., 2016). For example, Zhang et al. (2016) indicated that the placement of biochar in the middle layer of a sandy soil column significantly reduced the K_{sat} and increased the water retention of soil compared with the effects obtained with the uniform mixing of biochar in soil. Additionally, Li et al. (2016) found that the even mixing of 2% (w/w) biochar in the subsoil (10–20 cm) significantly enhanced the wetting front migration rate and the cumulative water infiltration amount in silty clay soil, but the uniform mixing of biochar into plow-layer soil (0–20 cm) significantly decreased the water infiltration amount. Similarly, other application methods in field conditions, such as top dressing or deep banding into the rhizosphere (Lehmann and Joseph, 2009), may also create heterogeneous soil structures that exert different effects on *K* compared with those obtained with uniform mixing (Liu et al., 2016). However, the effects of biochar application methods on N leaching and *K* are not well understood. Can we screen some appropriate biochar application methods that can optimize or balance the effects of biochar on N leaching and *K* in fine-textured soil?

As stated, we made the following hypothesis: (1) the addition of biochar to fine-textured soil may mitigate N leaching and affect *K*, but the effects depend on the application method, and (2) a high biochar addition rate may increase *K* and increase the leaching of N, especially as nitrate. The specific objectives of this research were the following: (1) to study the effects of methods of apple branch-based biochar on N leaching and *K* in silty clay soil, (2) to explore the relationships of N leaching and *K* under different biochar application methods, and (3) to identify an optimal biochar application method that can mitigate N leaching while increasing *K* in silty clay soil.

2. Materials and methods

2.1. Soil and biochar materials

This column-based study was conducted in a laboratory set up at the Institute of the *State Key Laboratory of Soil Erosion and Dryland Farming on the Loess Plateau,* Yangling, China. Bulk soil was collected from the 0-to-20-cm soil layer from Yangling (34°17′57″N, 108°04′06″E), air dried and ground to pass through a 2-mm sieve. The soil contained 17% clay, 73% silt and 10% sand and was thus considered silty clay according to the U.S. Department of Agriculture (USDA) system. The soil characteristics were as follows: soil pH 7.36, 1.20 $g\ cm^{-3}$ bulk density, 368.33 $\mu S\ cm^{-1}$ electrical conductivity (EC), 20.60 $cmol\ kg^{-1}$ CEC, 3.32 $g\ kg^{-1}$ total organic carbon, 0.47 $g\ kg^{-1}$ total N, 18.2 $mg\ kg^{-1}$ NO_3-, 15.90 $mg\ kg^{-1}$ NH_4^+, and 1.27 $mg\ kg^{-1}$ Olsen-P.

Biochar derived from apple branches (*Malus pumila* Mill) was produced by YIXIN Bioenergy Technology Co., Ltd. (Yangling, Shaanxi, China) through slow pyrolysis using a dry distillation method without any input of protective gas (e.g., N_2) into the carbonization system. The furnace temperature was ramped from ambient room temperature to 450 ℃ at a rate of 30 ℃/min and maintained at 450 ℃ for approximately 8 h. Finally, all biochar samples were crushed and ground to pass through a 2-mm sieve and then mixed thoroughly with soil, and the column was then filled with the soil mixture.

The physiochemical properties of the biochar are presented in Table 1, and the measurement methods have been described by Li et al. (2017). Briefly, the specific surface area of the biochar was tested using the Brunauer-Emmett-Teller (BET) method (Brunauer et al., 1938), and the N adsorption-desorption isotherms at 77 K were measured using an automated gas adsorption analyzer (Micro ASAP2460, Micromeritics, USA) (Hansen et al., 2016). The pH of the biochar was measured in 1:2.5 (w/v) biochar/Milli-Q water. The EC was determined in 1:5 (w/v; $g\ cm^{-3}$) biochar-water mixtures. The CEC was determined through passive barium exchange with forced magnesium exchange (Suliman et al., 2016). The elemental C, N, H and O concentrations of the biochar were determined using an elemental analyzer (Flash 2000, Thermo Fisher, USA). The total contents of K, P, Na, Ca, Mg, Fe, Cu, Mn and Zn were measured using an inductively coupled plasma (ICP) optical spectrometer (Vista Axial, VARIAN Medical Systems, USA).

Additionally, scanning electron microscope images were obtained to visually display the variations in the pore surface structure of the biochar (Supplementary Fig. S1). The variability in the functional groups of the biochar was investigated by Fourier transform infrared spectroscopy analysis (Supplementary Fig. S2). The equipment and procedures used for SEM and FTIR were previously detailed by Li et al. (2017).

2.2. Treatments and preparation of the soil columns

The experiment was conducted using three biochar application patterns and three levels of biochar amendments for each pattern. The three biochar application patterns involved the application of biochar to the following soil layers: A, the surface layer of soil (0–10 cm); B, the