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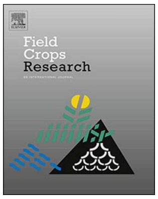

Effect of bentonite amendment on soil hydraulic parameters and millet crop performance in a semi-arid region

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ABSTRACT

We evaluated the effect of bentonite soil amendments on soil moisture, soil water storage, soil saturated hydraulic conductivity, water use efficiency and yield of millet in a field experiment in a sandy loam soil in a semi-arid region in northern China from 2011 to 2015. Treatments included six rates of bentonite amendments (0, 6, 12, 18, 24 and 30 Mg/ha) applied only in the first year. Adding bentonite amendments increased soil moisture, soil water storage and saturated hydraulic conductivity in the 0–60 cm layer. All bentonite amendments significantly ($P < 0.05$) increased above-ground biomass and grain yield, and improved water use efficiency in all five years. Above-ground biomass increases ranged from 2% to 39%, grain yield increases ranged from 3% to 20%, and water use efficiency increases ranged from 0% to 29%. The treatment with 24 Mg/ha bentonite had the greatest effect averaged over five years; the maximum bentonite rate treatment with 30 Mg/ha showed the greatest effect in the fifth year of the experiment. The treatment with 18 Mg/ha had the highest economic return over five years. Bentonite amendments show promise for improving soil water-holding capacity and crop yield in a semi-arid region, and therefore deserve further study.

1. Introduction

Climate change accompanied by climate variability and other extreme climate events will have a direct effect on the quantity and quality of agricultural production (Adams et al., 1998; Tilman et al., 2002; Maracchi et al., 2005), especially in semi-arid and arid regions where water scarcity is the most limiting factor for agricultural production. The quality and quantity of crop production is not only determined by total water amount and water use efficiency, but also is affected by rainfall distribution and water-holding capacity of soil (Banedjschafie and Durner, 2015). The region along the Great Wall in Inner Mongolia in northern China is a semi-arid area, where long-term intensive cultivation has led to serious soil degradation, including reduced soil water-holding capacity (Li et al., 2007). It is therefore necessary to take measures to combat drought stress and save water for sustainable agricultural production in these regions.

Millet (*Panicum miliaceum* L.) originated in China (Turrill, 1926) ; it has more than 8700 years of cultivation history (Lu et al., 2009) and is one of the longest- domesticated and most important crops in the world. Due to its high water use efficiency (Li et al., 2014), millet is one of main cultivated crops in the arid and semi-arid regions of all provinces of northern China between 32 – 48°N and 108 – 130°E. In this region, both millet grain yield and above-ground biomass yield are important as the above-ground residue is often used as livestock feed.

Nevertheless, drought and lack of water resource are the main limiting factors in millet production in this region. Therefore, improving the ability of soil to store water from limited precipitation, reducing evapotranspiration, and increasing water use efficiency, are essential strategies for sustainable development of rain-fed farmland. Recently, water-saving soil amendments have attracted attention for water management in agriculture production and studies on these types of amendments have shown an increase in water infiltration and water use efficiency in crops; as a consequence these improvements reduce irrigation water use and alleviate drought stress. They also reduce soil erosion by stabilizing soil structure (Green and Stott, 2001; Ajwa and Trout, 2006; Abrol et al., 2013).

Bentonite is phyllosilicate clay predominantly comprised of montmorillonite and therefore can be used as a natural and non-toxic soil amendment. Bentonite is abundant in China with over 8.0 Pg of proven reserves, and has a wide range of uses including drilling mud, sealing well casings, casting sand, iron ore pelletization and heavy metal absorption (Peng and Sun, 2012). However, reports of bentonite use in

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agriculture are relatively few. Previous studies on other clay amendments showed that their application increased soil water-holding capacity (Gill et al., 2004; Mojid et al., 2012; Tahir and Marschner, 2016) and water use efficiency in crops (Al-Omran et al., 2005), and reduced evapotranspiration (Zayani et al., 1996). These effects are likely due to increased soil aggregation, decreased soil bulk density, and improved soil porosity (Shao et al., 2005). Soil aggregation affects soil porosity and water-holding capacity, and aggregate size and stability affect soil fertility and crop growth (Shi et al., 2002). Other types of organic and synthetic polymer water-absorbing soil amendments have been studied with the objective of increasing soil water-holding capacity in semi-arid regions, but the results have been inconsistent (Ingram and Yeager, 1987; Tester, 1990; Green et al., 2004; Islam et al., 2011b).

We conducted field experiments to evaluate the effect of bentonite amendments on soil physical properties and millet crop performance over a five year period. Preliminary data on the amendment effect on soil moisture and yield over the first three years were presented at a scientific conference in 2014 and published in a non-peer reviewed journal (Mi et al., 2015).

The objective of this study was to evaluate the effect of different rates of bentonite amendments on spatial and temporal distribution of soil hydraulic properties including soil moisture, soil water storage, soil saturated hydraulic conductivity and water use efficiency, and millet above-ground biomass and grain yield in a semi-arid region of northern China over a five year period.

2. Materials and methods

2.1. Experimental site and design

The experimental field is located in Yijianfang village (39°57′ N, 111°39′ E) of Qingshuihe County, Hohhot, Inner Mongolia, China. The location is part of the Loess plateau with hilly-gully topography, typical of the proximate region. The region is semi-arid of mid-temperate zone with continental monsoon climate. The experiment field is flat, the average altitude is 1374 m above sea level, the mean annual temperature is 7.1 °C, the accumulated temperature ≥ 10 °C is 2370 °C-days, the frost-free period is around 140 d, the average annual evaporation is 2577 mm, and the annual rainfall is about 365 mm, which is concentrated mainly in July and August.

Long-term average climate data and daily mean temperature data were obtained from the Qingshuihe Weather Bureau in Hohhot, Inner Mongolia, China. Daily precipitation data were measured with rain gauge installed in the experimental field during the growing season. The total rainfall over the growing season was 189.6, 398.6, 520.2, 384.4 and 222.9 mm in 2011, 2012, 2013, 2014 and 2015, respectively.

The field experiment was conducted from 2011 to 2015, inclusive. The experimental design consisted of six treatments replicated on three randomized blocks. The treatments consisted of six rates of bentonite: 0, 6, 12, 18, 24 and 30 Mg/ha. Each plot was 6 m by 5 m. The treatments were applied only one time in spring 2011; the bentonite was broadcast with fertilizer prior to seeding and incorporated into the soil by cultivation.

2.2. Experimental protocol

Bentonite (Sanye Company, Tongliao, Inner Mongolia) had a chemical composition, on a weight basis of: 73.2% SiO_2, 11.4% Al_2O_3, 0.31% Na_2O, 2.67% CaO, 1.05% MgO, 2.58% K_2O, 0.29% Fe_2O_3, and the particle size was 75 μm. The cost was 63 United States Dollars (USD)/Mg.

Tillage consisted of spring ploughing at 20 cm depth for the first two years and about 30 cm depth (with a larger plough) in the final three years; this was followed by cultivating from 10 to 15 cm depth. Diammonium phosphate (DAP, N, P_2O_5, K_2O, 18-46-0) and Urea (46-0-0) as starter fertilizer were applied each year at 225 and 75 kg/ha respectively; additional urea was applied at 150 kg/ha at the jointing stage approximately 60 days after sowing. Millet was planted at the beginning of May and harvested in the middle of September in each of the five years (2011–2015). The millet variety was No. 5 Zhang, the seeding depth was 3–5 cm, the row spacing was 25 cm, and the planting density was 180,000–225,000 plants/ha. Two days after sowing, S-metolachlor herbicide was applied at 0.7–1.2 kg/ha AI (active ingredient) for weed control.

Table 1
The physical and chemical properties of the soil in the experimental site.

Property	Value
Texture	Sandy loam
Sand content (%)	72.8
Silt content (%)	13.4
Clay content (%)	13.8
Soil bulk density (g/cm^3)	1.42
Porosity (%)	43.65
Organic matter (g/kg)	10.96

2.3. Field and laboratory measurements

The descriptive baseline soil properties were measured according to standard methods (Gee and Bauder, 1986; Lu, 2000) and are shown in Table 1.

Soil samples for gravimetric soil moisture were collected at least three random positions in each plot using a manual soil auger, at depths of 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm at 1 d before sowing and 50, 70, 90, 110 and 130 d after sowing. The samples from each plot at same depth were mixed and the composite samples were oven-dried at 105 °C until constant weight.

Soil bulk density was also measured at 1d before sowing and at 50, 70, 90,110 and 130 d after sowing. A pit was excavated with horizontal ledges. A 10 cm diameter by 5 cm high cutting ring was inserted vertically into each ledge to take undisturbed soil samples of known volume for bulk density measurements corresponding to depths of 0–10, 10–20, 20–40, 40–60, 60–80, and 80–100 cm. Soil samples were oven-dried at 105 °C until constant weight.

Soil saturated hydraulic conductivity (K_{sat}) was measured in 2014 and 2015 with the constant-head method (Reynolds, 2006; Jiang et al., 2015). Undisturbed soil samples were taken from each plot from three random positions with a 10 cm diameter by 5 cm high cutting ring, at depths of 0–10, 10–20, 20–40 and 40–60 cm. A perforated bottom was placed underneath the cutting ring to stabilize the soil, and a second 5 cm high ring was placed on top of the cutting ring and sealed with tape to prevent water leakage. The cutting rings were placed over a beaker. Water was added in the upper ring and maintained at 5 cm head using the height of the upper ring as a guide. Leachate was periodically measured by dumping the beaker into a graduated cylinder. Flow rate was calculated for steady state conditions.

A 1 m^2 area of each plot was harvested by hand at maturity to determine above-ground biomass and grain yield. The millet grain price used for economic evaluation was 4.8 Chinese yuan/kg (roughly 0.72 USD/kg).

2.4. Data analysis

Saturated hydraulic conductivity (K_{sat}) was calculated by Eq. (1)

$$K_{sat} = V \cdot d/(T \cdot A \cdot h) \quad (1)$$

Where V is the volume of water (m^3), d is the soil thickness (m), T is the time of infiltration (seconds), A is the area of the ring (m^2) and h is the water head (m).