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Effects of different tillage practices on soil water-stable aggregation and organic carbon distribution in dryland farming in Northern China

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ABSTRACT

Knowledge about the changes in soil aggregate stability and soil organic carbon (SOC) under different tillage treatments is necessary to assess the feasibility of adoption of conservation practices for sustaining productivity and protecting the environment in dryland farming in northern China. In this study, four treatments, no-till with straw mulching (NTSM), all straw return tillage (ASRT), shallow rotary treatment (SRT) and conventional tillage (CT) were set and a 5 years field experiment was carried out to study the effects of different tillage practices on soil aggregates stability and organic carbon distribution. We found that macro-aggregate (>2 mm and 0.25–2 mm) proportion, mean weight diameter, total amount, content of SOC in macro-aggregate and proportion of SOC in macro-aggregate were significantly improved by NTSM, ASRT and SRT. In all treatments, soil ability to sequester carbon was improved more prominently in NTSM, and macro-aggregate proportion, mean weight diameter, total amount SOC in macro-aggregate and proportion of SOC in macro-aggregate were improve by 29.4%,30.9%,84.9% and 30.7% respectively by NTSM. In addition, improvement effects on soil aggregates stability and carbon sequestration ability in ASRT were all higher than in SRT, and compared to NTSM, macro-aggregate proportion was slightly higher (1.7%) in ASRT, but SOC content and amount in aggregates were remarkably lower. Our results revealed that reducing soil disturbance, increasing straw returning and especially their combined application (i.e. NTSM in this study) can effectively be used to reduce soil erosion and improve carbon sequestration in dryland farming in northern China.

1. Introduction

Stability of soil aggregates and soil organic carbon is the key indices for the soil quality of farmland ecosystems and the sustainable development of the environment [1–3], and they are greatly affected by tillage practices. Traditional tillage can accelerate the regeneration of macro-aggregates in surface soil, which affects the formation of micro-aggregates in the macro-aggregates and is detrimental to organic carbon sequestration in soil [4–7]. Therefore, no-till, reduced tillage, and straw return techniques, which focus on cost reduction, energy savings, and carbon sequestration, have received extensive attention [8,9]. More macro-aggregates (>250 μm) in no-tillage and straw returning soil are relatively well aggregated and stable and have a good protective effect on soil organic carbon [10,11]. Extensive studies have been conducted on different aspects of the dry farmlands of northern China (the types, the principles, and the ecological and economic benefits of tillage technology) [9]. However, there is a shortage of studies on the effect of tillage practices on the carbon sequestration mechanism and the potential for soil aggregates. Studies on the stability characteristics of soil aggregates and the organic carbon protection mechanisms of soil aggregates under different tillage practices are of great importance for determining the key factors and the primary mechanism for soil organic carbon sequestration with human intervention, increasing the soil organic carbon content, and improving soil quality. Therefore, a 5 year field experiment was carried out to research effects of various tillage practices, such as all straw return tillage (ASRT), no-till with straw mulching (NTSM), and shallow rotary treatment (SRT) on soil aggregates and organic carbon.

2. Research methods

2.1. Overview of the experimental field

The experimental field is located in the town of Zong'ai (37°51′N, 113°05′E; altitude: 1130 m) in Shouyang County, Shangxi, China, and has a warm temperate continental monsoon climate and situated in semi-humid and prone drought areas with a mean annual temperature of 7.4 °C, annual precipitation of 474 mm, annual evaporation of 1714 mm, and aridity of 1.3–1.49. The experiment began in 2004. The soil was cinnamon-brown and light loam, with a thick soil layer. At the beginning of the experiment, the concentrations of soil organic matter,

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total N, total P, available N, available P, and available K were 17.6 g/kg, 1.04 g/kg, 0.79 g/kg, 106.4 mg/kg, 15.0 mg/kg, and 117.2 mg/kg, respectively; the pH of the soil was 8.4.

2.2. Experimental design

There were a total of 4 treatments designed for the experiment — ASRT, NTSM, SRT and CT. Table 1 lists the detailed implementation schemes. There were 3 replicates for each treatment. The area of the experimental field was $10\ m \times 6\ m = 60\ m^2$. There was one crop each year of spring maize (variety: Qiangsheng No. 31), which was generally sown on approximately April 25 and harvested on approximately October 10 each year.

2.3. Test methods

Sampling was conducted after the harvest on October 11, 2008. For each treatment, there were 3 replicate sampling areas. The sampling depth was 0–20 cm. Undisturbed soil samples were collected in the field and then air-dried indoors. When the soil water content reached the plastic limit, the soil samples were gently broken into smaller pieces by hand along the natural structure. Plant residue and rocks were then removed. The samples were subsequently screened using an 8 mm sieve and then air-dried for further tests.

Soil aggregates were measured using the Elliott [12] wet screening method and classified into 4 groups: > 2000 μm, 250–2000 μm, 53–250 μm and < 53 μm. In addition, following Tisdall et al. [6], aggregates with a particle size of >250 μm were classified as water-stable macro-aggregates, and aggregates with a particle size of <250 μm were classified as water-stable micro-aggregates. After classification, the aggregates of all class sizes were collected, dried at 40 °C, and then weighed. The stability and the organic carbon content of each aggregate were measured. The potassium dichromate volumetric [13] method was used to determine the organic carbon content.

2.4. Data processing

After the data were processed using Excel, SPSS 17.0 was used for one-way analysis of variance (ANOVA). The least-significant difference (LSD) method was used for multiple comparisons among different treatments, and then, a t-test was performed ($P < 0.05$). SigmaPlot 10.0 was used to graph the results.

Table 1
Experimental treatments.

Treatment	Description of treatments
Tillage with all straw return (ASRT)	After the fall harvest, machines were used to directly till all the straw into the top 0–20 cm of soil. In the next spring, after the soil was compacted by machine shallow harrows, the seeds were manually sown. The amount of straw return was approximately 4500–6000 kg/hm^2.
No-tillage with straw mulch (NTSM)	After the fall harvest, all the straw was used to directly cover the soil surface in the field. In the next spring, the seeds were sown manually with no tillage. The amount of straw return was approximately 4500–6000 kg/hm^2.
Shallow rotary tillage (SRT)	After the fall harvest, 1/3 of the straw was left on the soil surface in the field. In the next spring, after shallow rotary tilling (5 cm) using machines, the seeds were sown manually. The amount of straw return was approximately 1500–2000 kg/hm^2.
Conventional tillage (CT)	After the fall harvest, all the straw was removed. Subsequently, before winter, the soil was deeply tilled (20 cm) using machines. In the next spring, after the soil was compacted by machine shallow harrows, the seeds were manually sown.

The mean weight diameter (MWD) is used to represent the stability of aggregates:

$$MWD = \sum_{i=1}^{n}(X_i \cdot W_i) \tag{1}$$

where X_i represents the mean diameter of the aggregates in the i^{th} sieve, and W_i represents the weight percentage of the aggregates in the i^{th} sieve.

The organic carbon storage of arable layer aggregates is calculated using the following equation:

$$M_{SOC} = M_S \cdot C_C \cdot 0.001 \tag{2}$$

where M_{SOC} represents the mass of organic carbon storage (kg/hm^2); M_S represents the unit area soil mass (kg/hm^2); and C_C represents the soil organic carbon content (g/kg).

The percent of the organic carbon in the arable layer aggregates is calculated using the following equation:

$$C_{SOC} = \frac{G_S \cdot C}{M_C} \times 100\% \tag{3}$$

where C_{SOC} represents the percent of the organic carbon in aggregates (%); G_S represents the organic carbon content in the aggregates of the particular size class (kg/hm^2); C represents the percent abundance of the aggregates of the particular size class (%); and M_C represents the organic carbon content in the arable soil (kg/hm^2).

3. Results

3.1. Effects of tillage practices on the distribution and stability of water-stable aggregates in soil

Table 2 shows that the tillage practices significantly affected the distribution of water-stable aggregates in soil. Compared with CT, the water-stable macro-aggregates under NTSM, ASRT and SRT increased by 29.4%, 39.7%, and 12.2%, respectively. ASRT primarily increased the abundance of aggregates with a particle size of >2 mm, whereas NTSM primarily increased the abundance of aggregates with a particle size of 0.25–2 mm; CT and SRT increased the abundance of aggregates with particle sizes of 0.053–0.25 mm and < 0.053 mm, respectively, indicating that there were differences in the distribution of water-stable aggregates in soil under different tillage practices.

Fig. 1 shows that ASRT, NTSM, and SRT could all significantly increase the stability of aggregates. The MWD of the soil aggregates was greatest under ASRT, followed by NTSM and SRT.

3.2. Effect of tillage practices on the organic carbon in water-stable aggregates in soil

Overall, the organic carbon content in the water-stable macro-aggregates in the classes >2 mm and 0.25–2 mm was significantly

Table 2
Size distributions of water-stable aggregates under different tillage practices (%).

Treatment	Macro-aggregate		Total	Micro-aggregate		Total
	>2 mm	0.25–2 mm		0.053–0.25 mm	<0.053 mm	
ASRT	23.0a	29.8b	52.8	25.1c	22.1bc	47.2
NTSM	19.7b	31.4a	51.1	28.9b	20.0c	48.9
SRT	14.6c	29.6b	44.3	26.2c	29.5a	55.7
CT	11.3d	28.2b	39.5	37.3a	23.1b	60.5

Notes: all straw return tillage (ASRT); no-till with straw mulching (NTSM); shallow rotary treatment (SRT); conventional tillage (CT); the lowercase letters on the same row indicate significant differences at the 5% level (LSD) within the layer under the different treatments (same below).