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Soil Aggregates Stability Response to Summer Fallow Tillage in Rainfed Winter Wheat Fields on the Loess Plateau

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Abstract: Soil aggregates are one of the most important indicators of soil quality, which can be affected strongly by soil tillage. Little is known about the composition and stability of soil aggregates under summer fallow tillage in rainfed winter wheat fields on the Loess Plateau. Soil aggregates were assessed before sowing and after the harvest of winter wheat under three tillage treatments during summer fallow, including minimum tillage (FMT), subsoiling (FST) and plough tillage (FPT). The results showed that the 0.25–2 mm soil mechanical-stable aggregates (MSA) under the FPT treatment were significantly higher (25.5–42.1%) compared with the FMT treatment in the 0–40 cm soil layer before sowing. The FMT treatment significantly increased the 0.5–2 mm size WSA content (24.6–342.4%) compared with the FPT treatment in the 0–20 cm soil layer before sowing and after harvesting. Compared with the FMT treatment, the FPT treatment significantly increased the stability of the MSA in the 0–20 cm soil layer before sowing and the FST treatment significantly increased the stability of the MSA in the 0–50 cm soil layer after harvest. The FPT treatment significantly decreased the geometric mean diameter (4.2–9.3%) and the stability rate (73.6–252.6%) and increased the destruction rate (1.3–3.5%) and the unstable aggregate index of the WSA (0.8–2.3%) in the 0–20 cm soil layer before sowing, compared with the FMT treatment. In summary, the application of FPT and FST increased the stability of the MSA in the 0–20 cm soil layer; however, FMT improved the stability of the WSA in the 0–40 cm soil layer.

Keywords: aggregate stability; rainfed winter-wheat; soil aggregates; summer fallow tillage

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1. Introduction

The world's drylands cover approximately 45% of the total land area [1] and are home to more than 38% of the world's population [2]. The global dryland area could increase by 11–23% by the end of the 21st century [3]. In China, drylands account for approximately 50.33% of the total cultivated land area [4]. It is necessary to improve grain production to ensure food security in dryland areas. Soil aggregates are an important indicator of soil quality, the composition and stability of which affect nutrient supply and storage. Farming practices, such as soil tillage, can strongly affect the composition and stability of soil aggregates, and consequently the growth and yield of crops.

Soil aggregates include mechanical-stable aggregates (MSA) and water-stable aggregates (WSA) [5]. Soil aggregates play an important role in protecting soil organic carbon (SOC) from mineralization and promoting SOC sequestration [6], as well as improving soil microbial communities [7] and water infiltration [8]. Soil tillage causes the fragmentation of soil macroaggregates and promotes an increase in soil microaggregates [9], changing the composition of soil aggregates. Conventional tillage can decrease the proportion of soil macroaggregates and increase the <0.25 mm soil aggregates [10]. Some studies concluded that the adoption of no-tillage promotes aggregate formation in surface soils and effectively increases the number of MSA [11] and WSA compared with conventional tillage [12]. Other studies suggested that the application of subsoiling can increase the WSA content in the 0–40 cm soil layer compared with conventional tillage [13] and increase the >0.25 mm WSA in the 0–5 cm soil layer compared with no-tillage [14]. Differences in the results may be related to site-specific conditions such as climate, soil texture, sampling time, cropping system, and tillage intensity.

In previous studies, the effect of tillage practices on the stability of soil aggregates has been controversial. In general, the adoption of no-tillage increased the mean weight diameter (MWD) of MSA and WSA in the topsoil [15,16]. However, some studies concluded that there was a small effect of no-tillage on the MWD and geometric mean diameter (GMD) of WSA in the 0–10 cm soil layer [17], or reduced MWD and GMD of MSA and WSA in the 0–5 cm soil layer [18]. In addition, subsoiling can increase the MWD of WSA in the 0–20 cm soil layer compared with conventional tillage [19] or have little effect [20].

Wheat is one of the three major food crops in China, and dryland wheat occupies an important position in agricultural production on the Loess Plateau. The sown area of wheat accounts for 15% of the total sown area of crop in Shanxi Province, and its yield accounts for 17% of grain production [21]. The sown area of dryland winter wheat accounts for approximately 60% of the total sown area of wheat in Shanxi Province [22]. However, the precipitation in the region is mainly concentrated in July–September, which is highly incompatible with the water requirement period of winter wheat. To solve this problem, water conservation technology has been proposed and widely applied, with deep plough/subsoiling during summer fallow as the core, which can effectively facilitate the summer precipitation into deeper soil layers, increase soil water storage in the 0–300 cm soil layer before sowing, and increase and stabilize the yield of winter wheat on the Loess Plateau [23]. Currently, the effect of summer fallow tillage on the composition and stability of soil aggregates is not clear. In this study, we hypothesized that summer fallow tillage will change the composition of MSA and improve the stability of MSA but reduce the stability of WSA. Therefore, we quantified the stability of MSA and WSA at a 0–50 cm soil depth. The objectives of this study were: (1) to analyze the effects of summer fallow tillage on the composition of MSA and WSA, (2) to investigate the mean weight diameter, geometric mean diameter, fractal dimension (D), destruction rate (PAD), stability rate ($WSAR$) and unstable aggregate index (E_{LT}) to assess the stability of soil aggregates in dryland wheat fields on the Loess Plateau.

2. Materials and Methods

2.1. Experimental Site Description

The experiment was initiated in 2011 at the Wenxi Experimental Station of Shanxi Agricultural University (111°28′ E, 35°35′ N), Yuncheng City, Shanxi Province, located in the eastern Loess Plateau (Figure 1). The region has a typical warm-temperate sub-humid continental monsoon climate, with an average annual temperature of about 12.6 °C, an average annual precipitation of 440 mm, an average annual sunshine duration of about 2461 h, and a frost-free period of 190 days. The predominant soil at the experimental site is classified as Calcaric Cambisols. Initially, the experimental soil of the 0–20 cm layer had a soil bulk density of 1.15 g cm^{-3}, a soil organic matter of 8.72 g kg^{-1}, a total nitrogen content of 0.78 g kg^{-1}, an alkali-hydrolyzed nitrogen content of 40.16 mg kg^{-1}, an available phosphorus of 19.87 mg kg^{-1} and a pH of 8.44. Winter wheat was grown generally from late September to early October and harvested from early June to mid-June in the drylands of the Loess Plateau. Summer fallow is from mid-June to late September, which receives 60–70% of the annual precipitation.

2.2. Experimental Design

Since 2011, the experiment has been conducted as a randomized complete block design with three treatments, including minimum tillage during summer fallow (FMT), subsoiling during summer fallow (FST), and plough tillage during summer fallow (FPT). Each plot size was 150 m^2 (3 m wide × 50 m long) with three replications, with a 1 m boundary between the plots. In all treatments, 20–30 cm of winter wheat stubble was left in the field at the time of winter wheat harvest.

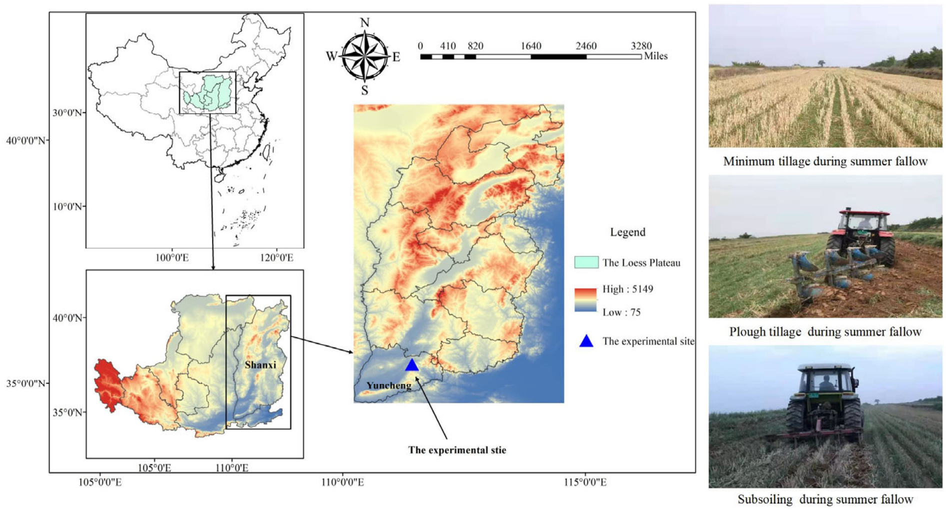

Figure 1. Location of the experimental site and tillage treatments during summer fallow.

All plots received 600 kg ha^{-1} of commercial organic fertilizer (≥45% SOM) before summer fallow tillage in the FPT and FST treatments after heavy rains in mid-to-late July. The subsoiler was used to break up and loosen the soil structure to a depth of approximately 30–35 cm, and synchronously the commercial organic fertilizer was applied through the pipes to a soil depth of approximately 20–25 cm in the FST treatment. The distance between the tines of the subsoiler was 50 cm. Most of the crop residues (from the previous harvest) were still left on the soil surface in the FST treatment. After the application of the commercial organic fertilizer on the soil surface, plough tillage was implemented to a depth of 25–30 cm in the FPT treatment, facilitating the burial of crop residues (from the previous harvest) into the soil. In addition, there was no tillage in the FMT treatment in mid-to-late July, which is a popular practice used among local farmers. In the FMT treatment, 600 kg ha^{-1} of commercial organic fertilizer (≥45% SOM) was applied before sowing. At the end of August, all treatments were harrowed (to a depth of approximately 15–20 cm) to prevent water loss and to bury weeds. Before sowing, all treatments received 600 kg ha^{-1} of compound fertilizer (N:P_2O_5:K_2O = 20:20:5). Winter wheat under the FST and FPT treatments was sown by using drill sowing beside a common film method, while under the FMT treatment wheat was sown by using the conventional drill-sowing method [24]. The two sowing methods have been described in the previous literature [24]. Here, winter wheat was sown into in rows 20 cm apart without film mulch in the conventional drill sowing method. In addition, ridging, common film mulching, seeding, and compaction were carried out simultaneously under the drill seeding using a common film method. The ridge was a circular arc with a height of 10 cm and a base of 40 cm, which was then mulched with plastic film (400 mm wide and 0.01 mm thick). The plastic film was covered with soil along both edges, and a seeder dug a furrow 10 cm wide and 5 cm deep. Winter wheat was sown in a side furrow in rows 40 cm wide and 20 cm apart. The winter wheat variety "Jinmai 47" was sown at a seeding rate of 97.5 kg ha^{-1}.

2.3. Sampling and Determination Methods

In the current study, undisturbed soil samples in the 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm and 40–50 cm soil layers were collected before sowing (September 2015) and after the harvesting (June 2016) of winter wheat, and the effect of short-term tillage during summer fallow on soil aggregates was evaluated. In this study, the temperature and precipitation at the experimental site from July 2015 to June 2016 are shown in Figure 2, which were obtained from the China Meteorological Science Data Sharing Service Network [25]. Undisturbed soil samples were stripped down to individual particles of <10 mm in diameter and placed in an aluminum box (length 30 cm, width 12 cm, height 10 cm). Soil samples were transported to the laboratory, air-dried, and used for soil aggregates analysis.

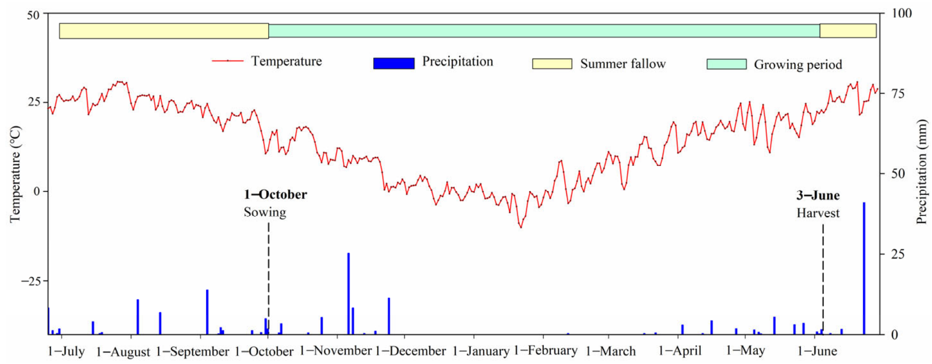

Figure 2. Temperature and precipitation at the experimental site.

Soil aggregates classification was determined by a combination of dry and wet sieving methods [26]. Briefly, 200 g of air-dried soil samples was weighed and placed on the top layer of the sieve set composed of 10 mm, 7 mm, 5 mm, 3 mm, 2 mm, 1 mm, 0.5 mm and 0.25 mm. The sieve set of MSA was gently shaken manually for approximately 5 min. The sieve assembly was shaken at the speed of once per second for approximately 40 s, then the top sieve was removed, and the remaining sieve assembly was shaken down to the bottom sieve. The contents of MSA of different sizes were collected by dry sieving and then the mass percentage of MSA of each size was then calculated (Equation (1)). According to the mass percentage of MSA of each size, 50 g of soil sample was weighed and placed in a 1 L sedimentation cylinder, which was usually immersed in the deionized water for 10 min. Then, deionized water was added to bring the volume back to 1 L of the sedimentation cylinder again, gently agitated with up and down movements 10 times, and the sample was transferred to the top layer of an automatic vibrating sieve set composed of 5 mm, 3 mm, 2 mm, 1 mm, 0.5 mm and 0.25 mm. The sieve set of WSA was gently shaken for 20 min at a speed of 25 times per minute. The contents of WSA of different sizes were obtained by wet sieving (Equation (2)).

$$w_{di} = \frac{W_{di}}{M_{d200}} \times 100\% \quad (1)$$

$$w_{wi} = \frac{W_{di}}{M_{d50}} \times 100\% \quad (2)$$

where w_{di} and w_{wi}, respectively, are the proportion of the weight of soil aggregates at particle size i (%) of mechanical-stable aggregates and water-stable aggregates, respectively; W_{di} is the weight of soil aggregates at particle size i (g); M_{d200} and M_{d50} are the total weighed soil weight (g) of mechanical-stable aggregates and water-stable aggregates, respectively.

The MWD_d and MWD_w (Equation (3)), GMD_d and GMD_w (Equation (4)), D_d and D_w value (Equation (5)), PAD (Equation (6)), $WSAR$ (Equation (7)) and E_{LT} (Equation (8)), which have been used as aggregate indices to assess soil aggregates stability, were calculated as previously described [27–29].

$$MWD_d(MWD_w) = \sum_{i=1}^{n}[\overline{x}_i \times w_{di}(w_{wi})] \quad (3)$$

$$GMD_d(GMD_w) = \exp\left[\frac{\sum_{i=1}^{n} w_{di}(w_{wi}) \times \lg\overline{x_i}}{\sum_{i=1}^{n} w_{di}(w_{wi})}\right] \quad (4)$$

$$(3 - D_d(D_w)) \times \lg\left(\frac{\overline{x_i}}{x_{\max}}\right) = \lg\left[\frac{W(\delta \le \overline{x_i})}{W_0}\right] \quad (5)$$

$$PAD = \frac{M_{d0.25} - M_{w0.25}}{M_{d0.25}} \times 100\% \quad (6)$$

$$WSAR = \frac{M_{w0.25}}{M_{d0.25}} \times 100\% \quad (7)$$

$$E_{LT} = \frac{M_t - M_{w0.25}}{M_t} \times 100\% \quad (8)$$

where MWD_d and MWD_w are the mean weight diameter (mm) of mechanical-stable aggregates and water-stable aggregates, respectively. GMD_d and GMD_w are the geometric mean diameter (mm) of mechanical-stable aggregates and water-stable aggregates, respectively. w_{di} and w_{wi} is the same as in Equations (1) and (2), $\overline{x_i}$ is the mean diameter of the sieve size class i (mm), n is the total number of fractions, D_d and D_w are the fractal dimension of mechanical-stable aggregates and water-stable aggregates, respectively. $W(\delta \leq \overline{x_i})$ is the sum of the soil weights with size $\leq \overline{x_i}$ (g), W_0 is the total mass of soil aggregates at each grain size (g), x_{max} is the diameter of the largest soil aggregates (mm), PAD is structure-deterioration rate (%), $WSAR$ is stability ratio of water-stable aggregates (%), $M_{d0.25}$ and $M_{w0.25}$ are the percentages of >0.25 mm mechanical-stable aggregates and >0.25 mm water-stable aggregates, respectively (g), E_{LT} is unstable aggregate index, M_t is the total weight of the soil (g).

2.4. Statistical Analysis

In this study, SPSS 16.0 software (SPSS Inc. Chicago, IL, USA) was used to perform analysis of variance and multiple comparison analysis for the difference among different tillage treatments. A new multiple range method (Duncan) was used for multiple comparisons ($p < 0.05$). The maps were created using ArcGIS 10.8 (ESRI Inc., California, LA, USA). The figures were drawn using Origin 2019b (Origin Lab, Corp., Northampton, MA, USA).

3. Results

3.1. Compositions of MSA

Both before sowing and after harvesting for winter wheat, the >0.25 mm MSA fraction accounted for more than 70% of the total MSA for all treatments (Figures 3 and 4). Before sowing for winter wheat, compared with the FMT treatment, the FPT treatment significantly increased the MSA content in the 7–10 mm and 5–7 mm aggregate size range by 42.7–58.5% and 53.9–57.6%, respectively, compared with the FMT treatment in the 0–20 cm soil layer, and significantly increased the 1–2 mm, 0.5–1 mm and 0.25–0.5 mm size by 22.4–71.3%, 35.1–101.8% and 39.0–118.1%, respectively, in the 20–40 cm soil layer. The 0.25–0.5 mm MSA under the FST treatment were significantly higher by 43.3–81.3% than those under the FMT treatment in the 20–50 cm soil layer. The >10 mm MSA content under the FMT treatment were significantly higher than those under the FPT treatment in the 10–30 cm soil layer.

After harvesting for winter wheat (Figure 4), the MSA under the FPT treatment significantly increased the >10 mm and 7–10 mm aggregate sizes compared with those under the FMT treatment in the 10–20 cm and 40–50 cm soil layers, respectively. The content of 0.25–0.5 mm MSA increased significantly by 19.0–50.2% compared with the FMT treatment in the 20–40 cm soil layer. The MSA content in the 0–30 cm and 40–50 cm soil layers significantly increased the >10 mm and 7–10 mm aggregate sizes under the FPT treatment compared with the FMT treatment, respectively. The 1–2 mm and 0.5–1 mm MSA content under the FMT treatment significantly increased by 17.6–123.7% and 21.9–138.8%, respectively, compared with those under the FST treatment in the 10–50 cm soil layer.

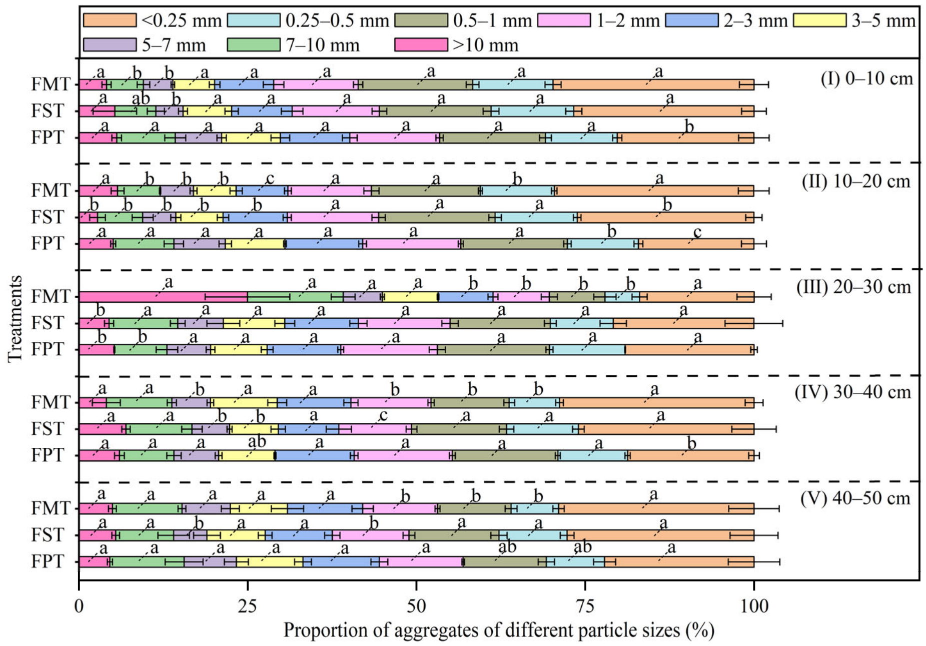

Figure 3. Effects of summer fallow tillage on the composition of soil mechanical-stable aggregates before sowing. FMT is minimum tillage during summer fallow, FST is subsoiling during summer fallow, and FPT is plough tillage during summer fallow. Lowercase letters indicate significant difference at $p < 0.05$ level among treatments. I, II, III, IV, and V indicate soil sampling depths of the 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm and 40–50 cm, respectively.

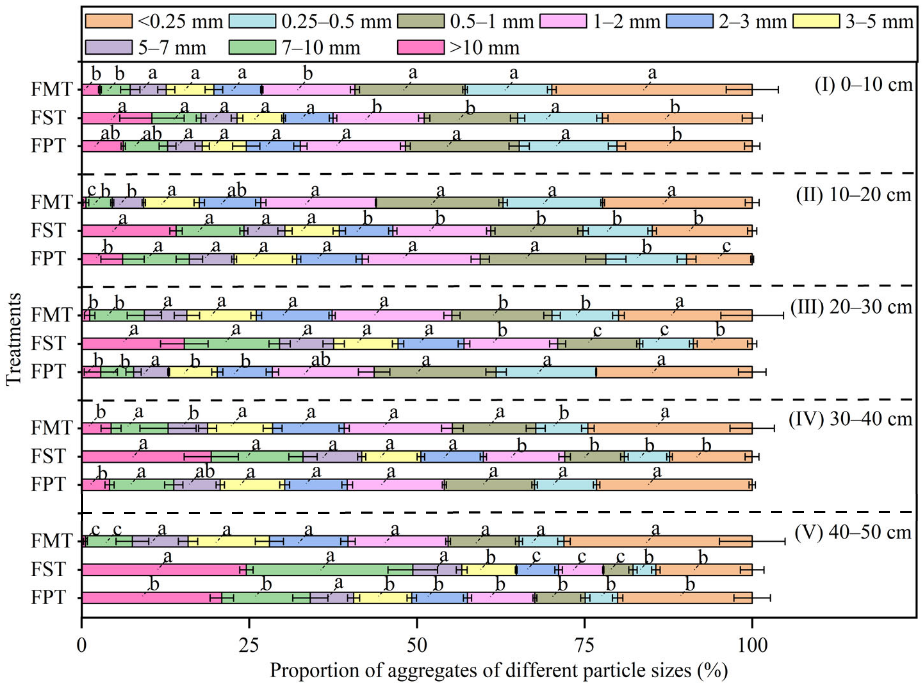

Figure 4. Effects of summer fallow tillage on the composition of soil mechanical-stable aggregates after harvesting. FMT is minimum tillage during summer fallow, FST is subsoiling during summer fallow, and FPT is plough tillage during summer fallow. Lowercase letters indicate significant difference at $p < 0.05$ level among treatments. I, II, III, IV, and V indicate soil sampling depths of the 0–10 cm, 10–20 cm, 20–30 cm, 30–40 cm and 40–50 cm, respectively.

3.2. Compositions of WSA

For all treatments, the <0.25 mm WSA content accounted for more than 75% of the total WSA before sowing (Table 1) and more than 80% after harvesting (Table 2). The WSA content under the FMT treatment significantly increased the 1–2 mm and 0.5–1 mm aggregate sizes compared with those under the FPT treatment in the 0–20 cm and 30–40 cm soil layers, respectively. The WSA content significantly increased the 2–3 mm and 1–2 mm aggregate sizes compared with the FST treatment in the 0–10 cm and 20–40 cm layers, respectively.

After harvesting (Table 2), the WSA content under the FMT treatment significantly increased the 2–3 mm and 1–2 mm aggregate sizes compared with those under the FPT treatment in the 0–20 cm and 30–40 cm soil layers, and significantly increased the 2–3 mm and 1–2 mm aggregate sizes compared with the FST treatment in the 0–40 cm soil layer. The WSA content under the FST treatment significantly increased the 0.5–1 mm and 0.25–0.5 mm aggregate sizes compared with those under the FPT treatment in the 0–20 cm and 40–50 cm soil layers.

3.3. The Stability of MSA

Before sowing (Figure 5), the FPT treatment significantly increased the MWD_d and GMD_d of MSA by 23.7–35.0% and 19.1–19.6%, respectively, and significantly decreased D_d by 2.2–4.8% in the 0–20 cm soil layer compared with the FMT treatment. The FMT treatment significantly increased the MWD_d and GMD_d of MSA in the 20–30 cm soil layer by 75.8% and 30.8%, respectively, compared to the FST treatment, and by 85.3% and 32.1% compared to the FPT treatment.

Table 1. Effects of summer fallow tillage on the composition of soil water-stable aggregates before sowing.

Soil Depth	Treatments	Percentage of Soil Aggregates of Different Particle Sizes (%)						
		>5 mm	3–5 mm	2–3 mm	1–2 mm	0.5–1 mm	0.25–0.5 mm	<0.25 mm
0–10 cm	FMT	0.56 ± 0.53 a	0.69 ± 0.26 a	1.14 ± 0.15 a	1.46 ± 0.03 a	4.38 ± 1.25 a	9.93 ± 2.42 a b	81.834 ± 3.96 b
	FST	0.48 ± 0.42 a	0.40 ± 0.13 b	0.44 ± 0.10 b	0.65 ± 0.17 b	3.35 ± 0.31 a b	12.39 ± 1.03 a	82.29 ± 1.50 b
	FPT	0.52 ± 0.49 a	0.69 ± 0.16 a	0.37 ± 0.10 b	0.33 ± 0.04 c	1.64 ± 0.27 b	6.91 ± 1.04 b	89.54 ± 1.45 a
10–20 cm	FMT	1.87 ± 1.09 a	0.92 ± 0.32 a	0.92 ± 0.35 a	1.26 ± 0.25 a	3.78 ± 0.71 a	8.51 ± 1.68 a	82.73 ± 2.85 b
	FST	0.01 ± 0.02 b	0.42 ± 0.36 a	0.52 ± 0.25 a	0.66 ± 0.27 b	3.30 ± 0.47 b	9.47 ± 1.82 a	85.63 ± 2.13 b
	FPT	0.00 ± 0.00 b	0.30 ± 0.28 a	0.40 ± 0.13 a	0.40 ± 0.07 b	1.54 ± 0.28 b	5.83 ± 1.00 b	91.54 ± 1.44 a
20–30 cm	FMT	1.44 ± 0.94 a	0.40 ± 0.36 a	0.65 ± 0.11 a	0.57 ± 0.13 a	1.97 ± 0.53 a	5.81 ± 1.59 b	89.15 ± 2.57 a
	FST	0.19 ± 0.34 a	0.18 ± 0.11 a	0.23 ± 0.07 b	0.36 ± 0.11 b	1.32 ± 0.17 a	5.84 ± 0.63 b	91.87 ± 0.48 a
	FPT	0.28 ± 0.44 a	0.32 ± 0.47 a	0.19 ± 0.04 b	0.50 ± 0.23 a b	1.96 ± 0.20 a	9.08 ± 1.44 a	87.67 ± 2.31 a
30–40 cm	FMT	1.08 ± 0.95 a	1.51 ± 1.05 a	0.92 ± 0.44 a	1.17 ± 0.40 a	4.15 ± 1.98 a	10.87 ± 7.60 a	80.30 ± 9.35 b
	FST	0.01 ± 0.02 a	0.44 ± 0.51 a	0.12 ± 0.06 b	0.16 ± 0.05 b	0.88 ± 0.05 b	5.01 ± 0.59 a	93.38 ± 0.10 a
	FPT	0.25 ± 0.22 a	0.14 ± 0.13 a	0.51 ± 0.41 a b	0.23 ± 0.03 b	0.98 ± 0.04 b	4.38 ± 0.63 a	93.51 ± 0.50 a
40–50 cm	FMT	2.43 ± 1.07 a	1.28 ± 0.46 a	0.87 ± 0.79 a	1.62 ± 1.30 a	4.03 ± 0.94 a	14.31 ± 1.31 a b	75.46 ± 3.33 b
	FST	0.44 ± 0.77 a	0.25 ± 0.43 b	0.21 ± 0.10 a	0.59 ± 0.47 a	4.36 ± 0.45 a	15.96 ± 2.03 a	78.19 ± 1.78 a b
	FPT	1.76 ± 0.07 a	0.61 ± 0.18 b	0.67 ± 0.41 a	0.77 ± 0.04 a	2.87 ± 0.36 b	11.59 ± 0.60 b	81.73 ± 0.77 a

FMT is minimum tillage during summer fallow, FST is subsoiling during summer fallow, and FPT is plough tillage during summer fallow. Lowercase letters indicate significant difference at $p < 0.05$ level among treatments.

After harvesting (Figure 5), the FST treatment significantly increased MWD_d by 50.5–146.7% and GMD_d by 20.7–61.6% and significantly decreased D_d by 2.9–6.2% compared with the FMT treatment in the 0–50 cm soil layer. Meanwhile, the MWD_d and GMD_d significantly increased by 28.1–113.8% and 21.2–53.3%, respectively, compared with the FPT treatment in the 20–50 cm soil layer. The FPT treatment significantly increased MWD_d by 29.0–70.9% and GMD_d by 14.9–30.8% and significantly decreased D_d by 2.9–6.4% compared to the FMT treatment in the 0–20 cm soil layer.

Table 2. Effects of summer fallow tillage on the composition of soil water-stable aggregates after harvesting.

Soil Depth	Treatments	Percentage of Soil Aggregates of Different Particle Sizes (%)						
		>5 mm	3–5 mm	2–3 mm	1–2 mm	0.5–1 mm	0.25–0.5 mm	<0.25 mm
0–10 cm	FMT	1.03 ± 0.06 a	0.86 ± 0.12 a	1.07 ± 0.22 a	1.13 ± 0.09 a	3.91 ± 0.42 a	10.68 ± 0.38 a	81.31 ± 1.59 c
	FST	0.51 ± 0.07 a	0.31 ± 0.04 b	0.29 ± 0.13 b	0.37 ± 0.04 b	2.15 ± 0.11 b	11.83 ± 1.46 a	84.53 ± 2.09 b
	FPT	0.00 ± 0.00 a	0.06 ± 0.01 b	0.23 ± 0.15 b	0.38 ± 0.11 b	1.13 ± 0.13 c	3.51 ± 0.26 b	94.70 ± 0.19 a
10–20 cm	FMT	0.41 ± 0.37 a	0.53 ± 0.43 a	0.80 ± 0.21 a	0.71 ± 0.05 a	2.54 ± 0.17 a	5.92 ± 0.22 b	89.10 ± 0.90 b
	FST	0.53 ± 0.51 a	0.20 ± 0.18 a	0.25 ± 0.05 b	0.53 ± 0.06 b	2.16 ± 0.12 a	8.39 ± 0.30 a	87.95 ± 0.97 a
	FPT	0.22 ± 0.04 a	0.40 ± 0.20 a	0.21 ± 0.18 b	0.57 ± 0.03 b	1.41 ± 0.30 b	3.10 ± 0.58 c	94.09 ± 0.89 a
20–30 cm	FMT	0.47 ± 0.24 a	1.05 ± 0.43 a	1.14 ± 0.44 a	0.67 ± 0.05 b	2.20 ± 0.38 a	6.31 ± 0.35 a	88.17 ± 0.92 b
	FST	0.76 ± 0.34 a	0.40 ± 0.33 b	0.37 ± 0.14 b	0.23 ± 0.01 c	1.10 ± 0.02 b	6.00 ± 0.17 a	91.13 ± 0.26 a
	FPT	0.18 ± 0.03 a	0.37 ± 0.09 b	0.89 ± 0.25 a b	0.86 ± 0.14 a	1.93 ± 0.18 a	5.33 ± 0.99 a	90.44 ± 1.12 a
30–40 cm	FMT	0.66 ± 0.35 a	1.29 ± 0.67 a	0.88 ± 0.25 a	1.05 ± 0.13 a	2.16 ± 0.15 a	7.84 ± 0.29 a	86.11 ± 0.86 c
	FST	1.29 ± 1.07 a	0.69 ± 0.36 a	0.49 ± 0.01 b	0.29 ± 0.06 b	1.19 ± 0.23 b	7.87 ± 1.50 a	88.19 ± 0.70 b
	FPT	1.16 ± 1.00 a	0.68 ± 0.12 a	0.35 ± 0.16 b	0.36 ± 0.08 b	1.34 ± 0.09 b	3.51 ± 0.45 b	92.61 ± 1.11 a
40–50 cm	FMT	0.51 ± 0.09 a	0.66 ± 0.47 a	1.09 ± 0.03 a	0.89 ± 0.19 a	2.16 ± 0.22 b	7.51 ± 1.42 c	87.17 ± 2.41 a
	FST	1.45 ± 0.93 a	0.47 ± 0.24 a	0.60 ± 0.33 a	0.75 ± 0.12 a	3.20 ± 0.35 a	13.60 ± 0.19 a	79.94 ± 1.10 b
	FPT	0.62 ± 0.53 a	0.35 ± 0.22 a	1.01 ± 0.35 a	0.77 ± 0.18 a	2.58 ± 0.18 b	9.24 ± 0.32 b	85.44 ± 0.77 a

FMT is minimum tillage during summer fallow, FST is subsoiling during summer fallow, and FPT is plough tillage during summer fallow. Lowercase letters indicate significant difference at $p < 0.05$ level among treatments.

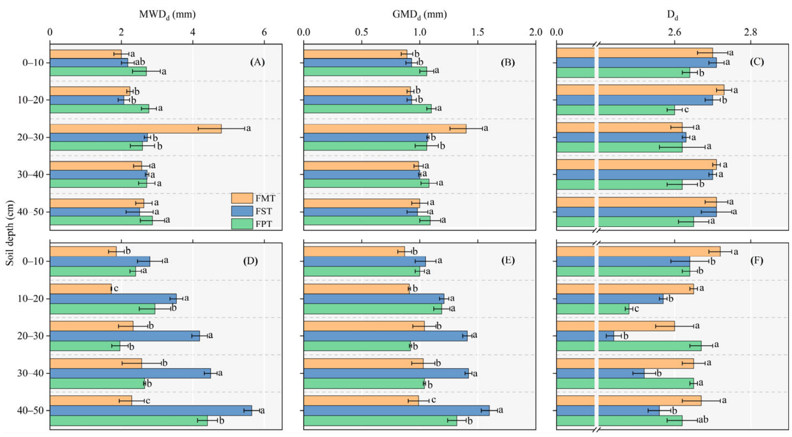

Figure 5. Effects of summer fallow tillage on MWD_d, GMD_d and D_d of soil mechanical-stable aggregates. FMT is minimum tillage during summer fallow, FST is subsoiling during summer fallow, and FPT is plough tillage during summer fallow. (**A**–**C**) indicate the sampling time before sowing of winter wheat. (**D**–**F**) indicate the sampling time after the harvest of winter wheat. Lowercase letters indicate significant difference at $p < 0.05$ level among treatments.

3.4. The Stability of WSA

Before sowing (Figure 6), the FMT treatment significantly increased MWD_w by 81.0–105.9% and GMD_w by 6.5–11.9% compared to the FST treatment in the 10–20 cm and 30–50 cm soil layers, which significantly increased MWD_w by 94.4–111.1% and GMD_w by 9.3–11.9% in the 10–20 cm and 30–40 cm soil layers and significantly decreased D_w by 0.7–1.3% in the 0–20 cm and 30–50 cm soil layers compared to the FPT treatment. The FST treatment significantly decreased D_w by 0.3–0.7% compared to the FPT treatment in the 0–20 cm soil layer. After harvesting, the FMT treatment significantly increased MWD_w by 19.2–85.0% in the 0–10 cm and 20–30 cm soils layers and significantly increased GMD_w by 2.0–8.3% compared to the FPT treatment in the 0–40 cm soil layer. The FMT treatment significantly decreased D_w by 0.3–1.3% compared to the FPT treatment in 0–40 cm soil layer. The FST treatment significantly decreased D_w by 0.3–1.0% compared to the FPT treatment in the 0–20 cm and 40–50 cm soil layers.

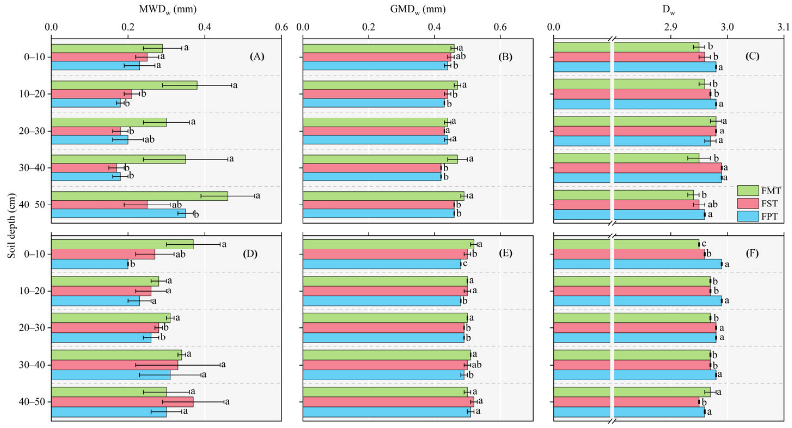

Figure 6. Effects of summer fallow tillage on MWD_w, GMD_w and D_w of soil water-stable aggregates. FMT is minimum tillage during summer fallow, FST is subsoiling during summer fallow, and FPT is plough tillage during summer fallow. (**A**–**C**) indicate the sampling time before sowing of winter wheat. (**D**–**F**) indicate the sampling time after the harvest winter wheat. Lowercase letters indicate significant difference at $p < 0.05$ level among treatments.

Before sowing of winter wheat (Figure 7), the FMT treatment significantly increased *WASR* by 34.3–203.5% and significantly decreased *PAD* by 1.8–3.3% and E_{LT} by 0.9–2.2% compared to the FPT treatment in the 0–20 cm and 30–50 cm soil layers. The FST treatment significantly increased the *WASR* by 69.3–69.9% and significantly decreased *PAD* by 1.6–1.9% and E_{LT} by 0.9–1.2% compared to the FPT treatment in the 0–20 cm soil layer. After harvesting, the FMT treatment significantly increased *WASR* by 23.7–252.6% and significantly decreased *PAD* by 0.6–3.5% and E_{LT} by 0.5–2.3% compared with the FPT treatment in the 0–40 cm soil layer. The FST treatment significantly increased *WASR* by 59.8–191.9% and significantly decreased *PAD* by 1.1–2.6% and E_{LT} by1.2–2.0% compared to the FPT treatment in the 0–20 cm and 30–40 cm soil layers.

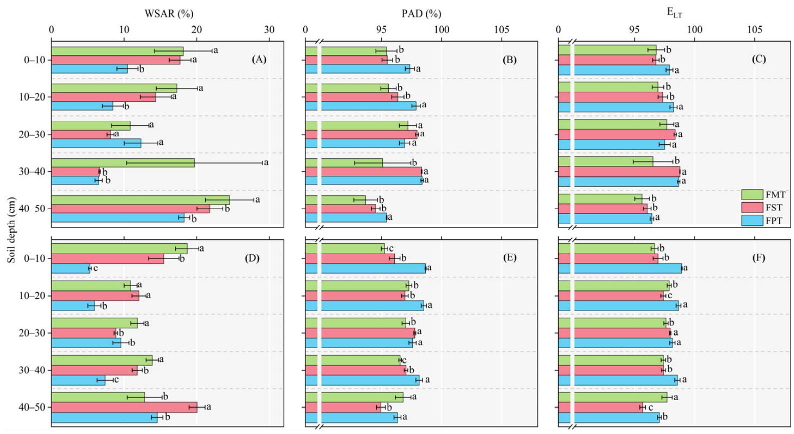

Figure 7. Effects of summer fallow tillage on *WASR*, *PAD* and E_{LT} of soil aggregates. FMT is minimum tillage during summer fallow, FST is subsoiling during summer fallow, and FPT is plough tillage during summer fallow. (**A**–**C**) indicate the sampling time before sowing of winter wheat. (**D**–**F**) indicate the sampling time after the harvest winter wheat. Lowercase letters indicate significant difference at $p < 0.05$ level among treatments.

4. Discussion

4.1. Compositions of Soil Aggregates and Summer Fallow Tillage

Aggregates of different sizes play an important role in nutrient storage, transport and transformation, and soil erosion [30,31]. In general, a higher proportion of >0.25 mm size aggregates indicates a more stable soil structure [32]. In the current study, the >0.25 mm

MSA content accounted for more than 70% of the total MSA, and the >0.25 mm WSA content accounted for less than 25% of the total WSA for all treatments, both before sowing and after the harvest of winter wheat. However, some studies concluded that the >0.25 mm MSA content was 53–70% of the total MSA for different tillage treatments [33], and the >0.25 mm WSA content was 35–66% of the total WSA [34,35]. The difference in the percentage of soil aggregates composition may be due to the site-specific differences in soil types, climatic conditions, cropping systems, and tillage managements.

4.2. The Stability of MSA and Summer Fallow Tillage

A reasonable distribution of soil aggregates is of great importance for agricultural production [27]. In general, soil disturbance can alter the composition of soil aggregates in the natural state and reduce the content of soil macroaggregates [28,29]. The *MWD* and *GMD* are common indicators used to evaluate the stability of soil aggregates, with larger values indicating better soil aggregates stability [36]. The *D* value is an important indicator for quantifying the particle size distribution of soil aggregates [37]. The results showed that the FPT treatment significantly increased the MSA content >0.25 mm in size and the MWD_d and GMD_d of MSA and decreased the D_d of MSA compared with the FMT treatment in the 0–20 cm soil layer before the sowing of winter wheat. This may be because the FPT treatment can bury the returned crop residues and commercial organic fertilizers in the 0–20 cm soil layer earlier than the FMT treatment, which could enhance the formation of soil macro-aggregates during and following their decomposition by soil microorganisms [38,39]. In addition, soil water is also an important factor affecting the formation and stability of soil aggregates [40,41], such as soil water content, soil water dynamics and the wetting–drying cycle. Our previous study showed that the FPT treatment can retain more precipitation in the 0–300 cm soil layer during summer fallow and increase the soil water content before sowing compared with the FMT treatment [23,42]. When soil moisture is high, the disintegrated aggregate pieces can reassemble after the rain event [43], resulting in the greater stability of soil aggregates before sowing due to the higher soil water content under the FPT treatment. There may be severe wetting–drying cycles under the FMT treatment before sowing, which could reduce the aggregate stability by a slaking effect [44,45]. However, it is necessary to obtain more evidence to clarify the effect of soil water on the stability of MSA in our further research.

This study also showed that after the harvest of winter wheat, the FST treatment significantly increased the MWD_d and GMD_d and decreased the D_d value of MSA in the 0–50 cm soil layer compared with the FMT treatment. This may be due to greater root biomass, root length density, and specific root length during the growing season of winter wheat under the FST treatment compared to the FMT treatment [46], which contribute to the formation and stabilization of soil aggregates through physical entanglement [47–49] and root–soil particle binding agents [50–52]. However, the MWD_d and GMD_d of MSA under the FPT treatment in the 20–50 cm soil layer after harvesting were lower than those under the FST treatment. This is due to the higher recovery capacity of the soil under the FST treatment, which only broke the plow pan and did not change the upper and lower soil sequence, resulting in the greater stability of MSA in the 20–50 cm soil layer after the harvest of winter wheat.

4.3. The Stability of WSA and Summer Fallow Tillage

A good soil structure should not only have a high MSA content but also a high WSA content [53]. This study showed that the FPT treatment significantly reduced the GMD_w and *WSAR* and increased the *PAD* and E_{LT} of WSA in the 0–20 cm soil layer before sowing compared with the FMT treatment. This may be due to a lower concentration of SOC as a cementing substance of soil aggregates under the FPT treatment [54], resulting in a decrease in the WSA stability. Numerous studies have concluded that application of the FPT treatment increased SOC mineralization compared with the FMT treatment [55,56]. In addition, soil water repellency is one of the important factors affecting the WSA stability. Lower soil water repellency under the FPT treatment could result in an increased wettability of soil aggregates [57], which decreases the WSA stability [58]. In the future, the relationship between WSA stability, SOC concentration and soil water repellency should be analyzed.

4.4. Limitations

In the current study, the commercial organic fertilizer was applied to all treatments during summer fallow; however, there were differences in the time, depth and placement of its application among the summer fallow tillage treatments. This could result in differences in the formation and stability of soil aggregates. Therefore, the effect of commercial organic fertilizer application on soil aggregate stability should be evaluated in future research. In addition, the conventional drill seeding method was used in the FMT treatment, while the FPT and FST treatments used drill seeding next to a common film method. The different sowing methods between treatments could lead to the difference in soil water content and plant root biomass in our study, which also influence the stability of soil aggregates. It is necessary to evaluate the influence of different sowing methods on the stability of soil aggregates in rainfed winter wheat fields. Furthermore, the SOC concentration could influence the formation and stability of soil aggregates, as there were generally greater influences of different tillage practices on the SOC concentration. The contribution of SOC concentration to the stability of soil aggregates was not analyzed in the present study; however, it is necessary to evaluate it in order to clarify the stability mechanisms of soil aggregates.

5. Conclusions

The composition and stability of soil aggregates before sowing and after the harvest of winter wheat under different tillage treatments during summer fallow were analyzed in this current study. It is concluded that compared with the FMT treatment, the stability of *MSA* was improved under the FPT treatment with higher MWD_d and GMD_d and lower D_d in the 0–20 cm soil layer before sowing and after harvesting, and also under the FST treatment with higher MWD_d and GMD_d and lower D_d in the 0–50 cm soil layer after harvesting. However, considering MSA and WSA, the application of FMT can improve the stability of soil aggregates with larger *WSAR* values and small *PAD* and E_{LT} values compared with FPT before sowing and after harvesting.

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