Organic Amendments to a Wheat Crop Alter Soil Aggregation and Labile Carbon on the Loess Plateau, China

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Abstract: The Loess Plateau in China is one of the most severely eroded areas in the world. Understanding the characteristics of soil aggregation and the distribution of soil organic carbon (SOC) in aggregates on the plateau is essential for improving regional soil quality. A 2-year study was conducted in a wheat cropping system on the plateau to investigate short-term responses of soil aggregation measured via water stability and total as well as labile SOC (permanganate-oxidizable C [POXC]) fractions to organic amendments (low-, medium-, and high-level maize stalks, stalk composts, and cattle manure) combined with inorganic fertilization (nitrogen/phosphorous/potassium [NPK]). Compared with NPK fertilization, combined organic amendments enhanced soil aggregate stability mostly for 5-to 0.5-mm size classes. Among the treatments, high-level maize stalk plus NPK was associated with the greatest water stability of all aggregates and lowest aggregate deterioration rate (11.3%), followed by cattle manure plus NPK (21.2%). In the 0- to 20-cm soil layer, the SOC content had no significant changes among treatments, whereas the POXC content was significantly higher in the organically amended treatments (especially cattle manure plus NPK, 108.6 %) than in the NPK treatment ($P < 0.05$). In most aggregate size classes, the SOC content had no significant differences between the organically amended and NPK treatments, whereas the POXC content was significantly higher in the former than in the latter ($P < 0.05$). There were significant positive relations between the proportions of water-stable aggregates and POXC content ($P < 0.05$). Application of high-level maize stalk or manure plus NPK was effective for improving soil structure and SOC sequestration of the loess soil.

Key Words: Loess soil, organic amendments, soil aggregation, soil organic carbon, permanganate-oxidizable carbon

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Soil aggregation, as a key indicator for soil structure, is a product of interactions between soil microbial communities and mineral-organic compositions. Maintaining high stability of soil aggregates is essential for improving crop productivity, preventing soil degradation, and minimizing environmental pollution (Mikha and Rice, 2004). The aggregation process is an important means for conserving and protecting soil organic carbon (SOC) pools, which allows the stored fractions of SOC to function as a reservoir of plant nutrients and energy for microorganisms (Bandyopadhyay et al., 2010). The distribution of SOC in aggregates of different size classes may affect the process of soil degradation, especially erosion.

The SOC content is a key factor that determines soil fertility and quality. At present, it remains difficult to measure minor quantitative changes in SOC pools caused by variations in soil management practices, despite that these changes may impose significant effects on soil properties and associated microbial processes (Weil et al., 2003). Alternatively, labile SOC is a relatively small fraction of SOC that responds quickly to changes in soil management and fertilization practices (Weil and Magdoff, 2004). The labile SOC fraction is an important component that determines soil quality for its involvement in soil aggregate stabilization (Tisdall and Oades, 1982) and direct link to soil carbon (C) and nitrogen (N) mineralization (Gunapala and Scow, 1998).

Culman et al. (2012) have recently suggested a more exact name of labile SOC used by the scientific community, "permanganate-oxidizable C" (POXC). Evidence shows that POXC has greater sensitivity than SOC to changes in management practices and microbial biomass C in 42% of the significant experimental factors examined by 12 studies (Culman et al., 2012). Melero et al. (2009) reported that POXC is the most sensitive and reliable indicator for evaluating the short- and long-term impacts of soil management practices on soil quality. Studies found that POXC quantified by a modified potassium (K) permanganate method (Weil et al., 2003) is sensitive to the changes in SOC content induced by organic amendments (Miles and Brown, 2011), cover crop treatments (Jokela et al., 2009), and high-residue cropping systems (Miles and Brown, 2011). Lucas and Weil (2012) reported that POXC determination is useful for identifying soils where improved SOC management is likely to increase grain productivity and further contribute to soil quality interpretations for producers. Measuring the POXC content of a soil is considered simple for estimating the labile SOC fraction (Culman et al., 2012; Lucas and Weil, 2012).

Numerous studies have examined the effects of long-term fertilization and other management practices on the aggregate-size distribution and aggregate-associated SOC levels. Six et al. (1999) and Rasool et al. (2008), respectively, reported that 50- and 32-year applications of organic manure or compost improve soil aggregation and associated SOC content. Aoyama et al. (1999) found that increased SOC level is a response to long-term manure application rather than the changes in plant biomass driven by manure addition. In addition, the application of mineral fertilizers promotes macroaggregation and SOC enrichment (Rasool et al., 2008; Lugato et al., 2010, Yu et al., 2012). However, little attention has been paid to the effect of short-term application of organic materials on soil aggregate distribution, associated SOC (especially labile fraction) content, and quantitative relationship of soil aggregate size distribution with SOC and labile SOC fractions.

The Loess Plateau in China is one of the most severely eroded areas in the world. Extensive soil erosion occurs on the plateau mainly due to frequent heavy summer rainstorms, long-term

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human activities, and highly erodible loess soils, resulting in low stability of soil aggregates and poor soil fertility and productivity (An et al., 2010). Recent studies have been conducted on the effects of deforestation on accelerated soil erosion in the Ziwuling Area of the Loess Plateau (Zheng et al., 2005; An et al., 2010). Less information is available on the distribution of SOC in different aggregate sizes on the Loess Plateau and its potential relation with soil aggregate stability. The above issues need to be investigated for improving soil health and sustaining agricultural production on the Loess Plateau.

In the present study, a 2-year experiment with various fertilization treatments was conducted in a wheat cropping system on the Loess Plateau. The objective were as follows: (i) to investigate the effects of organic plus inorganic amendments on soil aggregate size distribution; (ii) to determine the quantitative relationship of total and labile SOC (POXC) with soil aggregate size distribution; and (iii) to provide an optimal fertilization mode with improved C sequestration under the experimental conditions.

MATERIALS AND METHODS

Field Site Description

In September 2007, a field experiment was carried out at Ganjin Village, Heyang County, Shaanxi Province, southeast of the Loess Plateau, in Northwest China (N35°19′87″; E110°05′22″; 880 m above sea level). This experimental site has an average annual temperature of 10.0°C and a mean annual precipitation of 572 mm. The soil is classified as silt loam according to the US Department of Agriculture Textural Classification System and the soil type as a Chromic Cambisol according to the FAO-UNESCO soil map (FAO, 1974). Major physicochemical properties of 0- to 20-cm-depth surface soil samples were as follows: pH 8.24; organic matter 12.5 g · kg^{-1}; total N 0.81 g · kg^{-1}; Olsen-P 9.57 mg · kg^{-1}; available K 108 mg · kg^{-1}; soil bulk density 1.30 g · cm^{-3}. The winter wheat variety was Jinmai no. 47 (*Triticum aestivum* L.).

Experimental Design

The experiment was designed as a randomized block with three replications. Seven treatments were performed with or without mixed inorganic fertilizer and organic amendments: no fertilizer (control); inorganic N/P/K fertilizer (NPK); low-, medium-, and high-level maize stalks plus NPK fertilizer (LSNPK, MSNPK, and HSNPK, respectively); stalk compost plus NPK fertilizer (CNPK); and cattle manure plus NPK fertilizer (MNPK). The plot under each treatment was 4.5 × 6 m in size.

The dose of N, P, and K from inorganic and organic sources to crops is given in Table 1. For inorganic fertilization, urea, diammonium-phosphate, and potassium sulfate were used as the sources of N, P and K, respectively. For the LSNPK, MSNPK, and HSNPK treatments, maize stalks were applied annually at 3,750, 7,500, and 15,000 kg · ha^{-1} (air dried), respectively. The maize stalks contained 450, 9.2, 1.5, 11.8 g · kg^{-1} C, N, P, and K, respectively, on a dry weight basis and were mechanically chopped into approximately 4-cm pieces before incorporated into the soil.

For the CNPK treatment, the compost was fermented for 2 months at the experimental farm using a mixture of maize stalks, chicken manure, and microbial inoculum, then applied annually at 7500 kg · ha^{-1} (air dried). On average, the compost contained 300, 9.1, 3.6, and 6.5 g · kg^{-1} C, N, P, and K, respectively, on a dry weight basis.

TABLE 1. Nitrogen (N), Phosphorous (P), and Potassium (K) Contents of Inorganic Fertilizers and Organic Amendments for Treatments of the Cropping System (kg · ha^{-1})

Treatments	N	P	K
Control	0	0	0
NPK	150.0	39.3	49.8
LSNPK	150.0 ± 34.5*	39.3 ± 5.6	49.8 ± 44.3
MSNPK	150.0 ± 69.0	39.3 ± 11.3	49.8 ± 88.5
HSNPK	150.0 ± 138.0	39.3 ± 22.5	49.8 ± 177
CNPK	150.0 ± 68.3	39.3 ± 27.0	49.8 ± 48.8
MNPK	150.0 ± 142.5	39.3 ± 52.5	49.8 ± 184.5

*The contents of inorganic N/P/K fertilizer + amended maize stalks, organic manure, or compost.

Control: no fertilizer; NPK: inorganic N, P, and K fertilizer; LSNPK, MSNPK, and HSNPK: low-, medium, and high-level maize stalks plus NPK, respectively; CNPK: maize stalk compost plus NPK; MNPK: cattle manure plus NPK.

For the MNPK treatment, cattle manure was applied annually at 15 t · ha^{-1} (air dried). The manure contained 150, 9.5, 3.5, and 12.3 g · kg^{-1} C, N, P, and K, respectively, on a dry weight basis. All inorganic fertilizers and organic materials applied were incorporated into the soil to a plowing depth of approximately 20 cm before wheat sowing. The fields were conventionally tilled.

Soil Sampling and Analysis

At the end of May 2009, soil samples were collected from the seven treatments a week before winter wheat was harvested. Three bulk soil samples (approximately 1 kg each) were collected from each of the 21 plots at a soil depth of 0 to 20 cm for characterization of soil aggregation. Undisturbed samples were taken with a hand metal spade and gently fractured into 1- to 2-cm aggregates along natural break points. The three samples from each plot were thoroughly mixed by hand to form a composite sample (n = 21 in total). For other analyses (SOC and POXC in topsoil), seven soil cores (5-cm diameter) were collected from 0- to 20-cm depth. The seven cores from the same depth were bulked to form one sample per plot (n = 21 in total).

The soil aggregate distribution was determined using a manual dry sieving method (Nimmo and Perkins, 2002). Briefly, 500 g of air-dried, undisturbed soil was sieved through a nest of sieves having 10-, 7-, 5-, 3-, 2-, 1-, 0.5-, and 0.25-mm mesh size, so nine aggregate size classes are obtained (i.e., >10, 10–7, 7–5, 5–3, 3–2, 2–1, 1–0.5, 0.5–0.25, and <0.25 mm). Subsamples from each sieve were further ground to pass through a 1-mm sieve for other analyses (0.15 mm for SOC analysis). The stability of soil aggregates was determined by using a wet sieving method (Dane and Topp, 2002).

The SOC content was determined via potassium dichromate oxidation at 170°C to 180°C followed by titration with 0.1 mol · L^{-1} ferrous sulfate (Walkley and Armstrong Black, 1934). The POXC content was estimated by reaction with a dilute permanganate solution that contained 0.02 *M* potassium permanganate and 0.1 *M* calcium chloride (adjusted to pH 7.2 with 0.1 *M* sodium hydroxide) (Weil et al., 2003).

Data Analyses

For determination of the aggregate size distribution, the weight ratio of aggregates in each sieve to the total aggregates was calculated. In addition, the aggregate deterioration rate was defined to reflect the water stability of soil aggregates (He et al., 2007):

$$\text{Aggregate deterioration rate (\%)} = (M_d M_w) \times 100/M_d$$

where M_d is the content of >0.25-mm aggregates (dry sieved), and M_w is the content of >0.25-mm aggregates (wet sieved).

The C management index (CMI) is a useful parameter for evaluating the ability of management practices to improve soil quality. It is a sensitive indicator for the degree of changes in soil C dynamics of a given agrosystem relative to a more stable reference soil (Blair et al., 1995; Diekow et al., 2005). In the present study, the control plot in the cropping system without any fertilizers was used as a reference sample to calculate the CMI index:

First, a C pool index (CPI) was calculated,

$$\text{CPI} = \frac{\text{Total organic C content of sample } (\text{g kg}^{-1})}{\text{Total organic C content of reference sample } (\text{g kg}^{-1})}$$

Then, a lability index (LI) was obtained,

$$\text{LI} = \frac{\text{Lability of C in each sample}}{\text{Lability of C in reference soil}}$$

where

$$\text{Lability of C} = \frac{\text{Oxizable C by KMnO}_4}{\text{SOC-Oxizable C by KMnO}_4}$$

Finally, CMI was estimated,

$$\text{CMI} = \text{CPI} \times \text{LI} \times 100$$

Differences among treatments were determined by one-way analysis of variance. Fisher's least significant difference test was used to separate means at the $P < 0.05$ level of significance. Regression equations were used to establish the relationship between the proportions of >0.25-mm water-stable aggregates and the contents of SOC and POXC. All calculations were performed with the SPSS 13.0 software.

RESULTS

Soil Aggregate Size Distribution

The proportion of aggregates of more than 10 mm was generally lower in organically amended treatments (LSNPK, MSNPK, and MNPK) than in the NPK treatment, with the lowest value (19.4%) observed in the LSNPK treatment ($P < 0.05$, Table 2). The proportion of 5- to 3-mm aggregates decreased in the order: LSNPK > CNPK > MNPK > MSNPK > NPK > HSNPK > control. The LSNPK and MSNPK treatments both increased the proportion of aggregates compared with the NPK treatment, but only LSNPK resulted in a significant increase by 27.1% ($P < 0.05$). The proportion of 1- to 0.5-mm aggregates was significantly higher in the organically amended treatments (except CNPK and HSNPK) than in the NPK treatment ($P < 0.05$). The average proportion of <0.25-mm aggregates in all treatments was approximately 35%, with slightly lower values in the HSNPK and CNPK treatments than in the other treatments (Table 2). No significant changes were found in the proportions of other aggregate sizes (7–5 and 2–1 mm) among treatments ($P < 0.05$).

The proportion of water-stable aggregates of more than 5 mm was the highest in the CNPK treatment, 6.5%, significantly higher than that in the NPK treatment ($P < 0.05$) (Table 3). The proportion of 5–2-mm aggregates increased generally with organic amendments, with 78.0% significant increase in the HSNPK treatment compared with the NPK treatment. The proportions of aggregates with other sizes (2–1, 1–0.5, 0.5–0.25 mm) were, respectively, 4.4% to 31.0%, 16.3% to 59.6%, and 18.9% to 72.9% higher in the MSNPK, HSNPK, and MNPK treatments than in the NPK treatment. The aggregate deterioration rates of different treatments followed the order: HSNPK (11.2%) < MNPK and MSNPK (21.2%–22.0%) < CNPK (33.1%) < NPK and LSNPK (40.8%–44.4%) < control (53.4%). This trend was generally opposite to that in the proportions of >0.25-mm water-stable aggregates under these treatments (Table 3).

Surface Soil Organic Carbon Content

After 2-year treatments, the SOC content was 7.19 to 7.87 $g \cdot kg^{-1}$ in the 0- to 20-cm soil layer (Table 4). Except for the CNPK treatment, organically amended treatments had slightly higher SOC content than the NPK treatment, with the greatest increase (6%) found in the MSNPK treatment. However, there were no significant differences in the SOC content among the seven treatments. The POXC content of 0- to 20-cm surface soil significantly ranged from 641.8 to 1338.6 $mg \cdot kg^{-1}$ (Table 4), with higher levels observed in the organically amended treatments than in the control and NPK treatments ($P < 0.05$). As compared with that of the NPK treatment, the POXC content increased by 108.6%, 102.6%, 98.9%, 71.1%,

TABLE 2. Soil Aggregate Size Distribution Under Different Treatments of Inorganic Fertilizers and Organic Amendments

	Soil Aggregate Size Distribution, %								
Treatments	**>10 mm**	**10–7 mm**	**7–5 mm**	**5–3 mm**	**3–2 mm**	**2–1 mm**	**1–0.5 mm**	**0.5–0.25 mm**	**<0.25 mm**
Control	29.99a*	7.40a	2.61a	5.40b	0.48c	2.22b	10.75ab	4.5ab	36.64a
NPK	32.4a	6.78a	2.21a	5.54b	0.53bc	2.54ab	10.13b	4.36b	35.44a
LSNPK	19.38b	7.98a	3.44a	7.04a	0.64abc	3.67a	12.54a	4.80a	39.65a
MSNPK	29.60a	6.01ab	2.60a	5.68b	0.78a	3.30ab	11.83a	4.59ab	35.60a
HSNPK	32.88a	7.27a	2.41a	5.41b	0.74ab	2.75ab	10.33ab	4.38b	33.83a
CNPK	32.55a	7.97a	2.81a	5.95b	0.64abc	2.67ab	10.24b	4.32b	32.84a
MNPK	26.47a	5.53b	2.55a	5.94b	0.67abc	3.17ab	12.23a	5.06a	38.37a

*Means followed by different letters within the same column are significantly different at $P < 0.05$ by the least significance difference test.

Control: no fertilizer; NPK: inorganic N, P, and K fertilizers; LSNPK, MSNPK, and HSNPK: low-, medium-, and high-level maize stalks plus NPK, respectively; CNPK: maize stalk compost plus NPK; MNPK: cattle manure plus NPK.

TABLE 3. Water-Stable Aggregate Composition and Aggregate Deterioration Rate Under Different Treatments of Inorganic Fertilizers and Organic Amendments

	Water-Stable Aggregate, %						
Treatments	>5 mm	5–2 mm	2–1 mm	1–0.5 mm	0.5–0.25 mm	<0.25 mm	Aggregate Deterioration Rate, %
Control	3.66b*	3.11b	3.86c	6.76c	12.2b	70.5c	53.4
NPK	3.18bc	3.27b	4.80ab	9.93b	17.0ab	61.8bc	40.8
LSNPK	1.33c	3.33b	3.84c	9.76b	15.3b	66.5c	44.4
MSNPK	3.53b	4.29ab	6.29a	15.9a	20.3ab	49.8b	22.0
HSNPK	5.68a	5.82a	6.23a	11.6ab	29.5a	41.3a	11.2
CNPK	6.49a	4.97ab	4.29b	12.1ab	17.1ab	55.1bc	33.1
MNPK	3.85b	4.87ab	5.01ab	11.9ab	23.0ab	51.4b	21.2

*Means followed by different letters within the same column are significantly different at $P < 0.05$ by the least significance difference test.

Control: no fertilizer; NPK: inorganic N, P, and K fertilizer; LSNPK, MSNPK, and HSNPK: low-, medium-, and high-level maize stalks plus NPK, respectively; CNPK: maize stalk compost plus NPK; MNPK: cattle manure plus NPK.

and 66.9% in the MNPK, HSNPK, MSNPK, CNPK, and LSNPK treatments, respectively.

The POXC/SOC ratio under the NPK treatment (8.64) was similar to that under control (9.28), both notably lower than those of the organically amended treatments (14.15–17.80, Table 4). The CMI was higher in the five organically amended treatments (169.56–231.83) than in the NPK (95.46) and control treatments (100.00), with the highest value observed in the MNPK treatment (231.83, Table 4).

Aggregate-Associated Carbon Fractions

The aggregate-associated SOC in every aggregate size class of 0- to 20-cm surface soil was generally higher in the organically amended treatments than in the NPK treatment, followed by the control treatment (Table 5). The SOC content of aggregates of more than 10 mm was slightly higher in the organically amended treatments (6.25–7.18 g · kg^{-1}) than in the NPK treatment, with the greatest value found in the MSNPK treatment (7.18 g · kg^{-1}). The SOC content of 3−2-mm aggregates generally increased by 2.0% to 7.7% in organically amended treatments (LSNPK, MSNPK, CNPK, and MNPK) compared with that of the NPK treatment, but the differences were not statistically significant. The SOC content of 1- to 0.5-mm aggregates was significantly higher in the organically amended treatments than in the control treatment except for LSNPK and HSNPK treatments. The SOC content of aggregates of less than 0.25 mm was slightly higher in the organically amended treatments (8.04–8.92 g · kg^{-1}, except CNPK at 7.88 g · kg^{-1}) than in the NPK treatment, with no statistically significant differences ($P < 0.05$, Table 5). Among the nine aggregate size classes, the aggregate-associated SOC content was highest in the 1- to 0.5-mm size class for all treatments except for the control, LSNPK, and HSNPK treatments. By comparison, the content of aggregate-associated SOC was relative lower in aggregates of more than 10 and of 10–7 mm (Table 5).

In aggregates of different size classes, the POXC content was generally higher in the organically amended treatments than in the NPK and CK treatments (Table 6). The POXC content of aggregates of more than 10 mm was approximately 1.5- to 2.0-fold higher in the organically amended treatments (805.7–1,095.1 mg · kg^{-1}) than in the NPK treatment (572.3 mg · kg^{-1}) ($P < 0.05$), with no significant differences among the organically amended treatments ($P < 0.05$). The POXC content of 5- to 3-mm aggregates was the highest in the HSNPK treatment, 1,466.93 mg · kg^{-1}, significantly higher than that in the NPK treatment ($P < 0.05$). The POXC content of 1- to 0.5-mm aggregates increased significantly in the organically amended treatments compared with the NPK and control treatments ($P < 0.05$). The POXC content of aggregates of more than 0.25 mm was significantly higher in the MSNPK, HSNPK, and MNPK treatments than in the NPK treatment ($P < 0.05$), with no significant differences among these organically amended

TABLE 4. Carbon Pool Management Index (CMI) in 0- to 20-cm Surface Soil

Treatments	POXC, mg · kg^{-1}	SOC, g · kg^{-1}	POXC/SOC, %	LI	CPI	CMI
Control	667.59 c*	7.19 a	9.28	1.00	1.00	100.00
NPK	641.82 c	7.43 a	8.64	0.92	1.03	95.46
LSNPK	1071.23 b	7.57 a	14.15	1.61	1.05	169.56
MSNPK	1276.71 ab	7.87 a	16.22	1.89	1.09	207.06
HSNPK	1300.06 ab	7.49 a	17.36	2.05	1.04	213.79
CNPK	1098.09 ab	7.36 a	14.92	1.71	1.02	175.40
MNPK	1338.60 a	7.52 a	17.80	2.29	1.01	231.83

*Means followed by different letters within the same column are significantly different at $P < 0.05$ by the least significance difference test.

Control: no fertilizer; NPK: inorganic N, P, and K fertilizers; LSNPK, MSNPK, and HSNPK: low-, medium-, and high-level maize stalks plus NPK, respectively; CNPK: maize stalk compost plus NPK; MNPK: cattle manure plus NPK. POXC: permanganate oxidizable carbon; LI: lability index, CPI: carbon pool index.

TABLE 5. Aggregate-Associated Organic Carbon (SOC) Content Under Different Treatments of Inorganic Fertilizers and Organic Amendments

	Treatments	Size Classes, mm								
		>10	10–7	7–5	5–3	3–2	2–1	1–0.5	0.5–0.25	<0.25
SOC, g · kg^{-1}	Control	6.04b*	6.14a	6.91a	7.41a	6.79b	7.75a	7.87b	8.06ab	7.38b
	NPK	6.23ab	6.35a	6.94a	7.81a	7.65ab	7.52a	8.23ab	7.64b	8.03ab
	LSNPK	6.25ab	6.62a	7.26a	6.90a	7.80ab	8.34a	8.27ab	8.09ab	8.18ab
	MSNPK	7.18a	6.12a	7.34a	7.25a	8.11a	7.84a	8.60a	8.37ab	8.10ab
	HSNPK	6.50a	7.08a	6.06b	6.97a	7.55ab	8.24a	8.36ab	7.38b	8.92a
	CNPK	7.10a	6.38a	6.80a	7.08a	8.11a	7.56a	8.58a	8.19ab	7.88ab
	MNPK	7.06a	6.54a	6.87a	7.23a	8.29a	7.92a	8.68a	8.62a	8.04ab

*Means followed by different letters within the same column are significantly different at $P < 0.05$ by the least significance difference test.

Control: no fertilizer; NPK: inorganic N, P, and K fertilizer; LSNPK, MSNPK, and HSNPK: low-, medium-, and high-level maize stalks plus NPK; CNPK: maize stalk compost plus NPK; MNPK: cattle manure plus NPK.

treatments (P>0.05, Table 6). The content of POXC in small size aggregates (0.25−5 mm) was generally higher than that of large size aggregates (>5 mm), consistent with the results of SOC content.

Relationship Between Water-Stable Aggregates and Soil Carbon Fractions

Relationships between the SOC and POXC contents of 0- to 20-cm surface soil and the proportion of water-stable aggregates of more than 0.25 mm were analyzed to establish a regression equation. The SOC content (x) was related positively to water-stable aggregates (y), and the regression equation was $y = 23.838x - 135.11$ ($n = 7$, $r^2 = 0.2364$) (Fig. 1), whereas the mean POXC content was highly positively related to the mean proportion of water-stable aggregates of more than 0.25 mm ($n = 7$, $r^2 = 0.625$, $P < 0.05$) (Fig. 2). These results indicate that active C components were conducive to aggregate formation and stability.

DISCUSSION

Effects of Organic Amendments on Soil Aggregation

In the present study, results showed that the proportion of dry-sieved aggregates of more than 10 mm declined in organically amended treatments (LSNPK, MSNPK, and MNPK) than in the NPK treatment. Large aggregates (>10 mm) are not favorable for improving the soil structure and increase bulk density while reducing the water retention capacity (Ćirić et al., 2012). In addition, the proportion of aggregates of more than 0.25 mm decreased in the HSNPK and CNPK treatments compared with the NPK treatment (Table 2). A previous study by Imeson and Verstraeten (1989) reported that aggregates of more than 0.25 mm are efficient in accelerating crusting and soil erosion. That is, erosion causes water and soil loss as well as aggregate slaking (Green et al., 2005). Thus, application of inorganic fertilizer combined with organic fertilizer can decrease clods (>10 mm) and dispersed substances (<0.25 mm), further improving soil structure and create a supportive environment for plant growth. The amended organic materials could supply additional water-soluble, hydrolysable substrates and C to the soil, leading to production of microbial polysaccharides as well as aliphatic and aromatic compounds. The latter can increase aggregate cohesion, accounting for the increase in aggregate stability to mechanical breakdown (Bandyopadhyay et al., 2010).

In the present study, addition of organic materials (e.g., manure, straw, or a combination thereof) was more effective in increasing the SOC content than application of NPK fertilizer alone (Table 5). Likewise, Liu (2007) found that long-term inorganic fertilization, especially when combined with organic materials, plays an important role in increasing the

TABLE 6. Aggregate-Associated Permanganate Oxidizable Carbon (POXC) Content Under Different Treatments of Inorganic Fertilizers and Organic Amendments

Treatments		Size Classes, mm								
		>10	10–7	7–5	5–3	3–2	2–1	1–0.5	0.5–0.25	<0.25
POXC, mg · kg^{-1}	Control	612.13b*	473.43d	395.88c	520.61b	605.03b	605.98c	807.01b	699.97c	735.82b
	NPK	572.26b	520.56cd	403.40c	507.23b	670.45b	594.74c	866.52b	753.85c	819.20b
	LSNPK	855.42a	928.13bc	658.93bc	852.42ab	1095.14a	941.24bc	1415.41a	1358.27ab	1121.05ab
	MSNPK	826.51a	1260.70ab	1053.04a	969.98ab	1420.67a	1356.88a	1634.30a	1743.68a	1549.61a
	HSNPK	1020.03a	1471.51a	925.87ab	1466.93a	1402.12a	1260.63ab	1680.25a	1764.14a	1475.37a
	CNPK	805.70a	1180.73ab	951.53ab	784.92b	1330.56a	1225.46ab	1719.66a	1415.53ab	1184.65ab
	MNPK	1095.10a	1375.33ab	957.97ab	990.17ab	1408.87a	1279.46ab	1644.02a	1294.19b	1515.27a

*Means followed by different letters within the same column are significantly different at $P < 0.05$ by the least significance difference test.

Control: no fertilizer; NPK: inorganic N, P, and K fertilizer; LSNPK, MSNPK, and HSNPK: low-, medium-, and high-level maize stalks plus NPK; CNPK: maize stalk compost plus NPK; MNPK: cattle manure plus NPK.

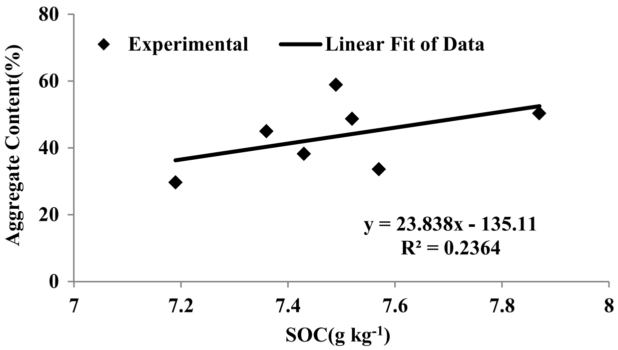

FIG. 1. The relationship between contents of >0.25-mm water-stable aggregates and SOC in 0- to 20-cm soil layer.

proportion of aggregates (2–5, 1–2, 0.5−1, and 0.25−0.5 mm) in surface soil. This is mainly because SOC is one of the main cementing agents of soil aggregates, which helps with large aggregate formation (2–5 mm). Previous work indicates that aggregate water stability plays a major role in improving soil fertility and grain production and that the application of compost increases the percentage of large water-stable aggregates (>5 mm) (Aoyama et al. 1999). Similar results were found in this study (Table 3). The aggregate deterioration rates decreased generally with organic amendments, showing a significant decrease by 72.5% in the HSNPK treatment compared with the NPK treatment (Table 3), which is in agreement with the finding by Huo et al. (2008). This phenomenon could be attributed to the increase in the SOC content after addition of stalks and subsequent formation of organic cementing materials (e.g., lignin and cellulose), which promoted the aggregate stability (Tisdall and Oades, 1982).

Relationship Between Soil Aggregation and Associated Carbon Fractions

In the present study, higher SOC and POXC fractions were observed in the 0- to 20-cm soil layer under organically amended treatments rather than NPK fertilization (Table 4). Similar observations have been reported in other agricultural systems (Qin et al., 2010). These observations could be attributed to the incorporation of organic materials with the soil, which likely resulted in the accumulation of organic matter in surface soil.

There were significant differences in the POXC content but not the SOC content between the organically amended and NPK treatments (Table 4). This result demonstrates that POXC is more sensitive to the changes in the soil C pool than SOC. In addition, POXC may have the ability to measure minor changes in management practices involving tillage and inputs after 2 to 4 years, as have been reported previously (Lewis et al., 2011; Lopez-Garrido et al., 2011).

The SOC content varied among aggregates of different sizes, and addition of organic materials generally increased the SOC content in all size classes of aggregates compared with control and NPK fertilization, especially in 3–2, 1–0.5, and 0.5−0.25 mm (Table 5). Among these organically amended treatments, cattle manure amendment plus NPK fertilization significantly increased the aggregate-associated SOC content (3–2, 1–0.5 mm) compared with the control treatment. Likewise, Yu et al. (2012) reported that organic manure increases the SOC content in all aggregates, and Huang et al. (2010) found that the application of manure alone or in combination with inorganic NPK fertilization greatly increased the SOC content in aggregates and improved soil aggregation, whereas inorganic NPK fertilization alone did not affect the SOC content in aggregates in a Chinese red soil. Together these findings indicate that the improvement effects of organic amendments on soil (including loess soil) are to some extent associated with soil type.

Our results showed that the SOC content of small aggregates was relatively high, which is consistent with previous findings in other soils (Bartoli et al., 1992; Barral et al., 1998). Holeplass and Lal (2004) found an increasing trend in the SOC content with decreasing aggregate sizes, whereas Saroa and Lal (2003) reported that the SOC content increases with increasing aggregate sizes. More recently, Huang et al. (2010) have found that the SOC content increases with increasing aggregate size in slightly eroded Ultisols and decreases with increasing aggregate size in moderately and severely eroded Ultisols. In the present study, soil samples were collected from severely eroded Loess Plateau soils containing less SOC. In this area, most of the cementing agents in macroaggregates are inorganic materials (Barral et al., 1998). Macroaggregate-associated organic materials could be stabilized and decompose rapidly because of their large aggregate size (Tisdall and Oades, 1982). Thus, the bonding strength developed within microaggregates is stronger than that within macroaggregates. Consequently, the distribution of SOC across the aggregate sizes varies perhaps because of different degrees of erosion.

Previous studies have found that low content of aggregate-associated SOC, especially labile SOC fraction, plays a decisive role in aggregate stabilization (Denef et al., 2007). In the present study, organically amended treatments had substantially higher POXC content in aggregates of most size classes compared with the NPK and control treatments, with no significant differences among the organically amended treatments (Table 6). This is probably due to the higher labile SOC inputs associated with the stalks and manure addition, as has been observed by Rudrappa et al. (2006). External organic amendments as well as increased fine root inputs provided more organic sources compared with the unfertilized treatment. Consistent with the results of aggregate-associated SOC content, the POXC content was higher in aggregates of smaller sizes (0.25–2 mm) than larger sizes (Table 6). Mikha and Rice (2004) reported that aggregate-protected labile C and N fractions were significantly greater for 0.25- to 2-mm aggregates in manure treatment than microaggregates (<0.25 mm) in chemical fertilization treatment and that 0.25- to 2-mm aggregates contribute more to relevant nutrient cycling. Thus, manure

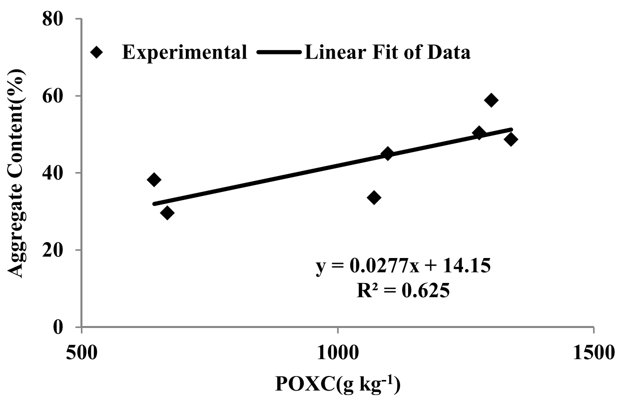

FIG. 2. The relationship between contents of >0.25-mm water-stable aggregates and permanganate-oxidizable carbon (POXC) in 0- to 20-cm soil layer.

amendments are management practices that can increase soil organic matter content and improve soil aggregation. According to Bandyopadhyay et al. (2010), the reason that small aggregates could hold a large amount of C is because of their extensive surface area and close distance to decomposed C.

The POXC-to-SOC ratio ranged from 9.3% to 17.8% in the loess soils (Table 4), generally within the range of data reported by Blair et al. (1995) and Rudrappa et al. (2006). Blair et al. (1995) proposed that CMI is a useful parameter to assess the status and rate of change in SOC pools in agricultural systems. This index is based on changes in easily oxidizable SOC, and total SOC resulted from various agricultural practices. C management index values have been calculated to get indications of C dynamics in agricultural systems (Yang et al., 2012). Despite the minor importance of its absolute values, the differences among CMI values reflect the effects of various management practices on different systems (Blair et al., 1995). In the present study, organically amended treatments led to substantial increases in the POXC content as a labile fraction of total SOC, further increasing the CMI values as compared with those of the NPK and control treatments. Hence, the shifts in C dynamics were likely caused by the addition of organic materials relative to those in chemically fertilized and unfertilized soils.

The SOC content can greatly contribute to aggregate formation, which accounts for approximately 70% to 90% of the variability in soil aggregate stability of a clay loam soil (Mbagwu and Bazzoffi, 1989). While total SOC is important in relation to soil aggregation, the more specific active fractions are directly involved in aggregation (Huang et al., 2010). These findings are consistent with our results presented in Figures.1 and 2. Li et al. (2006) reported that the low water stability of soil aggregates might have been caused partly by low SOC and low clay/silt content in desert soils in China, and the highest levels of total SOC and carbohydrates are recorded in soils with the highest aggregate stability (Zhang et al., 2008).

CONCLUSIONS

Compared with inorganic fertilizer (NPK), short-term application of organic materials (stalks, manure, and compost) combined with NPK in the wheat cropping system improved soil structure to different extents by regulating the soil aggregate distribution and stability. Meanwhile, the content of POXC rather than SOC significantly increased with organic fertilization compared with that with NPK fertilization only. The POXC content is highly sensitive to changes in SOC content induced by organic amendments, thus providing an early indication of soil health in response to management practices. The application of organic amendments generally increased aggregate-associated SOC and POXC contents compared with NPK fertilization. The contents of SOC and POXC in loess soil reduced gradually with increasing particle sizes, probably due to the increasing degree of erosion. Overall, the application of high maize stalk amounts or manure and NPK is most effective for improving soil structure and SOC sequestration under current soil conditions. A long-term comprehensive evaluation is needed to verify the most suitable and sustainable management practice for improving soil quality and organic carbon sequestration on the Loess Plateau in China.

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