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Soil Amendment Combining Bentonite and Maize Straw Improves Soil Quality Cropped to Oat in a Semi-Arid Region

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Abstract: Soil amendments have been proposed as an effective way to enhance soil carbon stocks on degraded soils, particularly in dryland farming areas. Soil organic carbon (SOC) plays an important role in improving soil quality, and soil aggregates are known to be crucial in sequestering and protecting SOC. However, how aggregation and protection of SOC by aggregates respond to a single application of bentonite combined with maize straw remains unknown, especially in the sandy soil of a semi-arid region. A three-year field experiment with four treatments [no amendment (CK), maize straw amendment addition only (T1, 6 Mg ha^{-1}), bentonite amendment addition only (T2, 18 Mg ha^{-1}), and maize straw combined with bentonite amendment (T3, 6 Mg ha^{-1} maize straw plus 18 Mg ha^{-1} bentonite)] was conducted in the Loess Plateau of China to assess the effects of bentonite and maize straw on aggregation and SOC. The results indicated that soil bulk density decreased by 2.72–5.42%, and soil porosity increased by 3.38–8.77% with three years of T3 application, especially in the 20–40 cm layer, compared with CK. T3 increased the amount of C input, SOC stock, and SOC stock sequestration rate by 1.04 Mg ha^{-1} y^{-1}, 0.84–1.08 Mg ha^{-1}, and 0.49 Mg ha^{-1} y^{-1}, respectively, and it increased the mass proportions and aggregate-associated C stock of >0.25 mm aggregates by 1.15–2.51- and 1.59–2.96-fold compared with CK. Correlation analysis showed a positive correlation of total SOC stock with the C concentration of >2 mm, 0.25–2 mm, and 0.053–0.25 mm aggregates. Aggregates of various sizes in sandy soils have the potential for greater SOC stock. Our findings suggest that the application of maize straw (6 Mg ha^{-1}) combined with bentonite (18 Mg ha^{-1}) would be an effective management strategy to enhance the bulk soil C pools by improving the soil structure and thereby improving soil fertility.

Keywords: bentonite; organic carbon; maize straw; soil aggregation; soil amendments

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1. Introduction

Dryland farming in China makes an important contribution to China's food production [1]. The Loess Plateau in northwest China is a typical dryland farming area. This region has mainly sandy soil with poor soil fertility and limited rainfall, which negatively affect soil quality and crop productivity [2]. Soil organic carbon (SOC) sequestration has been considered a potential pathway to improve soil quality and enhance the sustainability of dryland farming [3,4].

Soil aggregates are important carriers of organic carbon sequestration and turnover [5,6]. The size, quantities, and composition of aggregate fractions have been considered to be sensitive to changes in SOC, and they can serve as potential indicators of C sequestration under different soil management practices [7–12]. In previous studies, SOC concentration improved mainly from crop residues and other exogenous organic matter inputs to soils [13,14]. These materials directly or indirectly participated in the formation of soil aggregates, promoted the accumulation of organic carbon, and affected SOC stock [15,16]. However, their effectiveness in some soils has been questioned, such as those soils with low clay content and low water content [17–19]. One alternative to mitigate these problems could be applying amendments consisting of organic matter (i.e., straw) combined with clay minerals (i.e., illite, kaolinite, montmorillonite, etc.). Organic–mineral interactions have been regarded as the primary mechanism for the stabilization of SOC over decadal to millennial timescales [20,21]. The newly put-forward concept of the soil mineral carbon pump (MnCP) [22] further emphasized that minerals are important in increasing soil OC accumulation and persistence. Soil minerals can enhance the stability of SOC by transforming plant- or microorganism-derived labile OC into more stable forms in abiotic ways. These pathways are mainly adsorption, occlusion, aggregation, redox reactions, and polymerization [22–24]. However, their impact might differ among soils with different clay mineralogy [25,26]. Bentonite is a 2:1 clay mineral with montmorillonite as the main component. Previous research has shown that the addition of bentonite increased the C concentration in each aggregate size class [27]. Previous studies by our research team have also confirmed that a one-time application of bentonite in semi-arid areas could improve soil structure, preserve soil water, and effectively increase the SOC concentration and stock capacity of sandy soil [28,29]. Additionally, bentonite has potential co-benefits, such as reducing water and nutrient loss and increasing crop yield [30–34]. The permanent effect of the improvement of sandy soil chemistry through bentonite addition was also evaluated in a 38-year long-term plot experiment [35].

Plant-derived OC is a predominant source of SOC that enters the soil in different forms, either as straw, root, and stubble or as rhizodeposition. Oat (*Avena sativa* L.) is an important grain forage crop, and intercropping and crop rotation with maize (*Zea mays* L.), potato (*Solanum tuberosum* L.), soybean (*Glycine max* Merr.), and other crops have generally been practiced in regions with lower soil fertility and low rainfall; these factors limit production in oat monocropping. Improving soil parameters that promote crop-derived C input to the soil is a basis for maintaining or increasing SOC, which both improves soil health and fosters sustainable crop production.

Studies have determined the separate effects of maize straw and bentonite application on soil SOC, but few reports have examined the combined effects of maize straw applied along with bentonite on soil aggregate C stock in dryland farming. We hypothesized that there is a great advantage to enhancing aggregation in sandy soils and SOC stock when maize straw combined with bentonite is applied to oat cropping in dryland areas of the Loess Plateau in China.

2. Materials and Methods

2.1. Experimental Site and Climate

A field experiment was conducted from 2018 to 2021 at Yijianfang village of the Qingshuihe County Research Centre (39°57′ N, 111°39′ E), Hohhot, Inner Mongolia, China, which is located in the Loess Plateau of China. The experimental area is characterized by a semi-arid climate, and the experimental site comprises loess sandy loam soil; detailed soil property data are shown in Table 1.

Table 1. Basic soil property data of the experimental site (0–20 cm soil depth).

Soil Properties	Value
pH	7.62
Sand content (%)	72.8
Silt content (%)	13.8
Clay content (%)	13.4
Total nitrogen (g kg^{-1})	0.43
Available nitrogen (mg kg^{-1})	42.2
Available phosphorus (mg kg^{-1})	7.20
Available potassium (mg kg^{-1})	106.5

2.2. Experimental Design and Management

The field experiment was conducted from 2018 to 2021. The experiment was arranged with four treatments and three replicates. The treatments were (1) no amendment (CK), (2) maize straw addition only (T1, 6 Mg ha^{-1}), (3) bentonite addition only (T2, 18 Mg ha^{-1}), and (4) maize straw combined with bentonite (T3, 6 Mg ha^{-1} maize straw plus 18 Mg ha^{-1} bentonite). Each plot was 15 m $\times$ 8 m. Each year, 109.5 kg of N ha^{-1} and 103.5 kg of P_2O_5 ha^{-1} were applied as basal fertilizer.

Oat straw used as forage was completely removed from the plots after the grain harvest, and around 5–10 cm of stubble was left in the field. The straw in the amendment treatments was maize (*Zea mays* L.) straw from another field. The maize straw was air-dried, chopped into 5–7 cm lengths, and uniformly distributed over each plot. The maize straw was applied every year from 2018 to 2021; the bentonite was applied only once in 2018, and it was not applied in 2019–2021. Bentonite and maize straw were broadcast after harvest and then incorporated through moldboard ploughing to a 20–30 cm depth.

The bentonite was provided by the Sanyan Company in Tongliao, Inner Mongolia, China. The composition of the main chemical compounds on a weight basis were 73% SiO_2, 11% Al_2O_3, 0.3% Na_2O, 3% CaO, 1% MgO, 3% K_2O, 0.3% Fe_2O_3, and 0.69% organic matter. The oat variety was "Bayou 1", and it was planted at the beginning of June and harvested in the middle of September in each of the three years. The seeding depth was 3–5 cm, the row space was 25 cm, and the planting density was 375 plants m^{-2}.

2.3. Crop Biomass Measurements and Carbon Input Estimates

Oat above-ground straws were manually harvested from the center (1 m^2) of each plot in 2019–2021. Straws were oven-dried at 60 °C for biomass determination. For oat, the C concentration in the straw biomass was assumed to be 40% [36,37]. The amount of below-ground residue, including roots and rhizodeposition, was estimated from the ratio of roots to straw biomass, and the roots were estimated to equal 20% of the oat straw biomass [38]. The amount of residue and C derived from rhizodeposition was assumed to be equal to that originating from roots [39]. The oat grain and above-ground straw were removed at harvest in our experiment, but the stubble remaining in the field was estimated to be 10% of the oat straw biomass. The total plant-derived biomass and C concentration, including straw, stubble, roots, and rhizodeposition, were estimated based on the above information [40,41].

2.4. Soil Sampling

Soil samples were collected after oat harvest in 2019–2021. After the surface crop residue was removed, soil samples were taken with a spade at depths of 0–20 cm and 20–40 cm. The three soil samples from each plot at the same depth were thoroughly mixed and homogenized to form one composite sample for each layer (0–20 cm and 20–40 cm). Each sample was mixed thoroughly and passed through a 5 mm sieve by gently breaking the soil clods and avoiding soil deformation from mechanical compression. Pebbles, plant residues, and larger soil fauna were removed, and the soil was air-dried at room temperature. A portion of the subsample was used to investigate the soil organic matter, and the remaining soil was used to determine the aggregate size distribution.

2.5. Aggregate Size Distribution

The dry-sieve method was used to separate soil aggregates into four size fractions: (i) >2 mm, (ii) 0.25–2 mm, (iii) 0.053–0.25 mm, and (iv) <0.053 mm. Briefly, 100 g of air-dried soil samples was placed in a mechanical shaker (Octagon 200, Endecotts Company, South Wimbledon, UK) with three sieves (2, 0.25, and 0.053 mm) and shaken for 3 min. After sieving, each aggregate size was collected and weighed and then used for the determination of the C concentration.

2.6. Analysis of Soil Characteristics

The soil bulk density (g cm^{-3}) (BD) at 0–20 cm and 20–40 cm layers was measured by collecting undisturbed soil samples using cutting rings of known volume, 100 cm^3, and 5.046 cm in diameter. Three core samples were taken at random from each plot. The C concentration of the bulk soil and >2 mm, 0.25–2 mm, 0.053–0.25 mm aggregates and bentonite were determined according to potassium dichromate ($K_2Cr_2O_7$) oxidation [42].

$$M_{soil,i} = BD_i \times T_i \times 10000 \quad (1)$$

$$M_{element} = [\sum_{i=1}^{n} M_{soil,i} \times conc_i + \left(M_j - \sum_{i=1}^{n} M_{soil,i}\right) \times conc_{i+1}] \times 0.001 \quad (2)$$

$$AM_{element} = [\sum_{i=1}^{n} M_{soil,i} \times conc_i + \left(M_j - \sum_{i=1}^{n} M_{soil,i}\right) \times conc_{i+1}] \times P_i \times 0.001 \quad (3)$$

where $M_{soil,i}$ is the soil mass (Mg ha^{-1}) of the i^{th} layer (i = 1 or 2, representing the depths of 0–20, 20–40 cm, respectively). BD_i and T_i are the bulk density (g cm^{-3}) and thickness (m) in the i^{th} layer, respectively. $M_{element}$ represents the C stock of bulk soil and $conc_i$ and $conc_{i+1}$ are the concentrations of SOC in the i^{th} and $i + 1^{th}$ layer (g kg^{-1}), respectively. M_j is the maximum soil mass from the first layer to the n^{th} layer under different treatments. $AM_{element}$ represents the C stock of the i^{th} size aggregate, and P_i is the proportion of different sizes of aggregates.

The change in SOC stock in soil in the 0–20 cm layer from the start of the experiment in 2018 to the end in 2021 was calculated using the following equation:

$$\Delta SOC\left(Mg\ ha^{-1}\right) = SOC_c - SOC_i \quad (4)$$

where ΔSOC represents the change in SOC, SOC_c represents the C stock at the completion of the experiment in 2021, and SOC_i represents the C stock at the beginning of the experiment in 2018.

2.7. Statistical Analysis

Statistical analyses were carried out using Microsoft Excel 2019 (Microsoft, Redmond, WA, USA) and SAS version 9.4 (SAS Institute Inc., Cary, NC, USA). One-way ANOVA and Duncan's Multiple Range Test (DMRT) at a 5% level of significance were used to evaluate the variables in treatments. Regression analysis and Pearson's correlation matrix methods were performed using the software Origin 2022b (OriginLab Inc., Northampton, MA, USA). Simple regression analysis was used to quantify the relationships among the response variables (C input and C stock of bulk soil and aggregates); Pearson's correlation matrix was used to quantify the relationship among soil properties. Principal component analysis (PCA) was conducted using CANOCO 5 software (Microcomputer Power, Ithaca, NY, USA).

3. Results

3.1. Soil Bulk Density

After three years, BD was higher in the 20–40 cm layer than in the 0–20 cm layer (Figure 1A). Porosity showed an opposite decreasing trend with increasing depth in 0–40 cm soil layers (Figure 1B). Only the T3 treatment had significantly decreased BD compared with CK ($p < 0.05$), and it was reduced by 2.72% at 0–20 cm and by 5.42% at the 20–40 cm depth. T1, T2, and T3 treatments improved soil porosity in different soil layers. At 0–20 cm, only the T3 treatment had significantly increased the porosity by 3.38%. At 20–40 cm, there was no difference in porosity between T1, T2, and T3, but it increased by 7.57%, 6.50%, and 8.77%, respectively, compared to CK ($p < 0.05$). Collectively, the T3 treatment had a significant effect on decreasing BD and increasing porosity compared to CK.

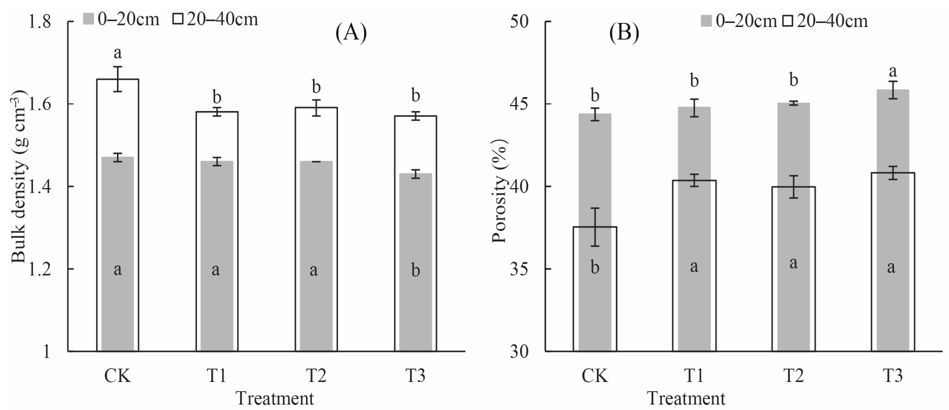

Figure 1. Changes in soil bulk density (**A**) and porosity (**B**) after harvest in 2021 in the 0–20 and 20–40 cm layers under addition of maize straw and bentonite amendments (mean ± SD, n = 3). Treatments at the same depth and capped with the same lowercase letter are not significantly different at the 0.05 probability level.

3.2. C Input, SOC Stock, SOC Sequestration Rate, and SOC Sequestration Efficiency

Over the three-year experimental period, the total C input in CK, T1, T2, and T3 treatments was 1.85, 4.46, 2.45, and 4.98 Mg ha^{-1}, respectively (Table 2). After three years, the T1, T2, and T3 treatments showed an increase in SOC stock in the 0–20 cm depth compared with the initial values, and the change in SOC (ΔSOC) was 0.98, 0.42, and 1.37 Mg ha^{-1}, respectively. The ΔSOC of T1, T2, and T3 was higher than that in CK by 1.06, 0.50, and 1.45 Mg ha^{-1}, respectively (Table 3). Meanwhile, the SOC stock sequestration rate was increased by 0.36, 0.17, and 0.49 Mg ha^{-1} y^{-1}, respectively (Table 3). The T3 treatment had the greatest influence on the C input, ΔSOC, and SOC stock sequestration rate.

Table 2. C input for three years.

Treatment	Maize Straw [1]	Bentonite [2]	Oat Straw	Root [3]	Stubble [4]	Rhizodeposition [5]	Total
Biomass (Mg ha^{-1})							
CK	0.00	—	9.24 ± 0.11 c	1.85 ± 0.02 c	0.92 ± 0.27 c	—	2.77 ± 0.03 d
T1	6.00	—	10.32 ± 0.29 b	2.06 ± 0.06 b	0.85 ± 0.30 b	—	9.10 ± 0.09 b
T2	0.00	—	11.87 ± 0.24 a	2.37 ± 0.05 a	0.98 ± 0.35 a	—	3.56 ± 0.07 c
T3	6.00	—	12.55 ± 0.66 a	2.51 ± 0.13 a	1.04 ± 0.37 a	—	9.77 ± 0.20 a
C input (Mg ha^{-1}) [6]							
CK	0.00	0.00	0.00	0.74 ± 0.01 c	0.41 ± 0.00 d	0.74 ± 0.01 c	1.85 ± 0.02 d
T1	2.40	0.00	0.00	0.83 ± 0.02 b	0.45 ± 0.01 c	0.83 ± 0.02 b	4.46 ± 0.06 b
T2	0.00	0.072	0.00	0.95 ± 0.02 a	0.52 ± 0.01 b	0.95 ± 0.02 a	2.45 ± 0.05 c
T3	2.40	0.072	0.00	1.00 ± 0.05 a	0.55 ± 0.03 a	1.00 ± 0.05 a	4.98 ± 0.13 a

[1] Straw represented the amount of maize straw amendment applied to the field. Data are mean ± SD, n = 3. The means in the same column and attributes with the same lowercase letters are not significantly different at the 0.05 probability level. [2] C concentration for bentonite was 0.4%. [3] Roots estimated equal to 20% of oat straw biomass [33]. [4] Stubble estimated equal to 10% of oat straw biomass. [5] C concentration from rhizodeposition was assumed to be equal to root biomass C at harvest. [6] C concentration was assumed to be 40% of oat straw biomass.

Table 3. Effect of maize straw and bentonite treatments on SOC stock and C input levels in the 0–20 cm layer.

Treatment	SOC Stock ($Mg\ ha^{-1}$)				ΔSOC [2] ($Mg\ ha^{-1}$)	SOC Stock Sequestration Rate ($Mg\ ha^{-1}\ y^{-1}$)
	2018 [1]	2019	2020	2021		
CK	10.62 ± 0.18 a	11.27 ± 0.02 c	10.85 ± 0.45 c	10.54 ± 0.20 c	−0.08 ± 0.12 b	−0.03
T1	10.11 ± 0.62 a	11.79 ± 0.07 b	11.33 ± 0.07 ab	11.1 ± 0.04 b	0.98 ± 0.58 a	0.33
T2	10.52 ± 0.19 a	11.63 ± 0.18 b	11.2 ± 0.11 bc	10.94 ± 0.25 b	0.42 ± 0.21 ab	0.14
T3	10.25 ± 0.81 a	12.11 ± 0.12 a	11.72 ± 0.10 a	11.62 ± 0.14 a	1.37 ± 0.85 a	0.46

[1] SOC stock was measured after the harvest of the oat in 2018. Data are mean ± SD, n = 3. The means in the same column and followed by the same lowercase letters are not significantly different at the 0.05 probability level.
[2] ΔSOC indicates change in SOC stock from 2018 to 2021.

3.3. Aggregate Size Distribution

Over the three-year experimental period, the largest proportion of soil aggregates was 0.053–0.25 mm, followed by 0.25–2 mm, >2 mm, and then <0.053 mm for all treatments at a 0–40 cm depth (Figure 2). The mass proportions of >2 mm and 0.25–2 mm aggregates increased with increasing soil depth, and the mass proportion of 0.053–0.25 mm aggregates decreased with increasing soil depth. Compared with CK, maize straw and bentonite treatments increased the proportions of >2 mm and 0.25–2 mm aggregates and decreased the proportions of <0.25 mm aggregates, but they had little effect on the proportion of <0.053 mm aggregates in 0–20 and 20–40 cm layers. Only very small amounts (less than 1%) of this particle size fraction were obtained during the “dry sieving method” process (Figure 2), and, consequently, the <0.053 mm size fraction was not considered in further analyses.

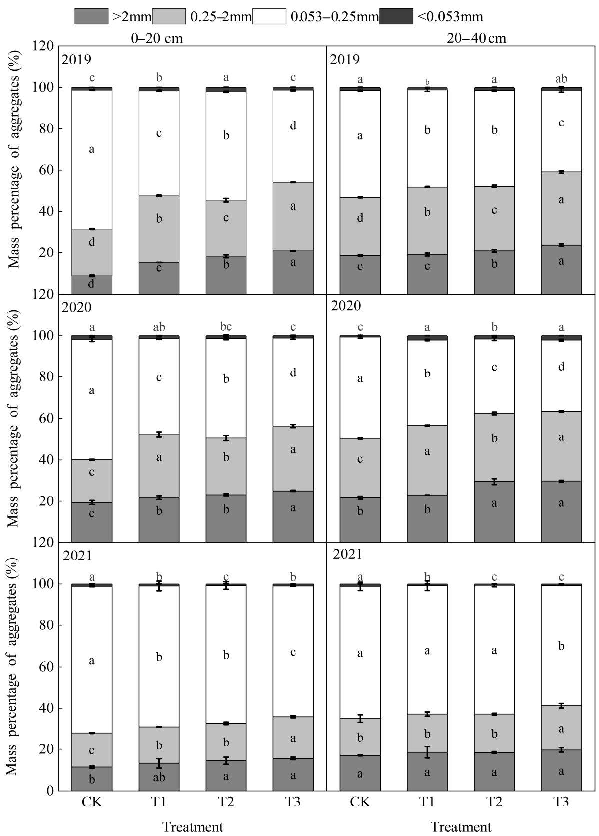

Figure 2. Mass percentage of aggregate size distribution in the 0–20 cm and 20–40 cm layers under maize straw and bentonite soil amendment treatments (mean ± SD, n = 3). The columns in the same year and depth and with the same lowercase letters are not significantly different at the 0.05 probability level.

3.4. Aggregate-Associated C Concentration and Stock

Over three years, the aggregate C concentration was higher at the 0–20 cm depth than at the 20–40 cm depth (Figure 3). The highest C concentration of soil aggregates was 0.25–2 mm, followed by >2 mm, and 0.053–0.25 mm was the lowest ($p < 0.05$) for all treatments at the 0–40 cm layer. The application of maize straw and bentonite improved the C concentration of different sizes of aggregates over the CK treatment in different soil layers, and the T3 treatment exhibited the largest increase from 14.09% to 38.14% over that of the other treatments over three years.

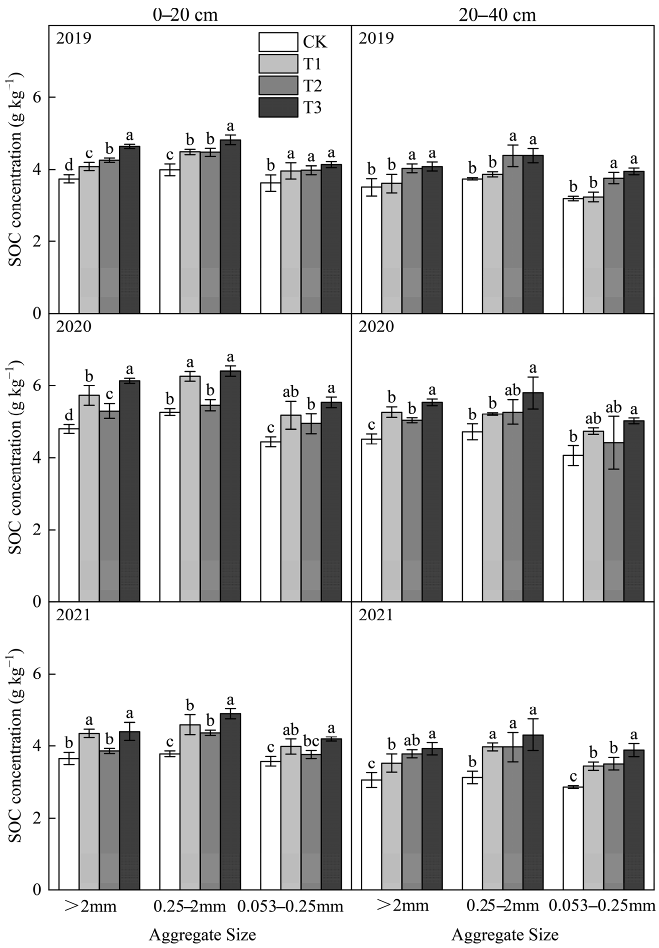

Figure 3. SOC concentration (g kg^{-1} aggregate) of different sizes of aggregates in the 0–20 cm and 20–40 cm layers under maize straw and bentonite soil amendment treatments (mean ± SD, $n = 3$). The columns in the same year and the same aggregate size and capped with the same lowercase letters are not significantly different at the 0.05 probability level.

The C stock was highest at 0.053–0.25 mm, followed by 0.25–2 mm and then >2 mm aggregates in all treatments at the 0–40 cm layer (Figure 4). Compared with CK, all of the T1, T2, and T3 treatments significantly increased the C stock of >2 mm and 0.25–2 mm aggregates ($p < 0.05$) and significantly decreased the C stock of 0.053–0.25 mm aggregates ($p < 0.05$) (except for no significant difference in 2021). The T3 treatment had the greatest effect over the three years.

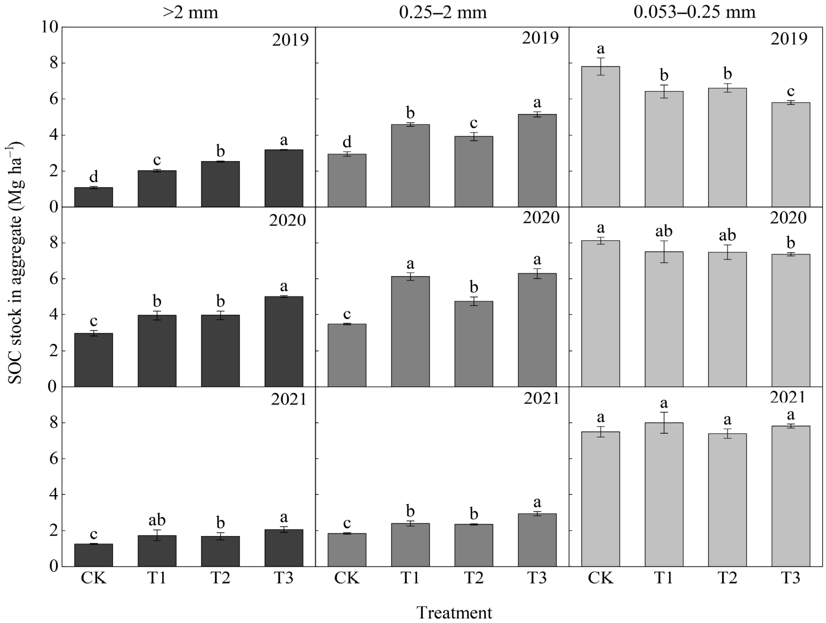

Figure 4. SOC stock of different sizes of aggregates affected by maize straw and bentonite soil amendment treatments in the 0–20 cm layer (mean ± SD, n = 3). The columns in the same year and the same treatment and capped with the same lowercase letters are not significantly different at the 0.05 probability level.

3.5. Relationships between Annual Average C Input and Aggregate C Stock

There was a significant positive correlation between SOC sequestration and annual average C input (Figure 5), indicating that the dryland farming areas in the Loess Plateau in China still have potential for SOC sequestration.

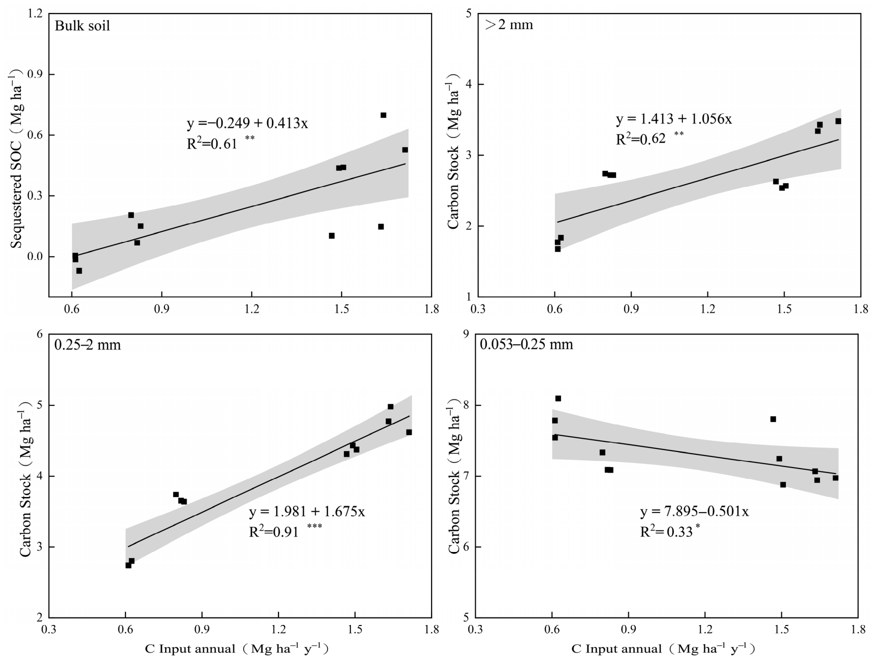

Figure 5. Relationships between annual average C inputs and sequestered SOC of bulk soil and C stock of the different sizes of aggregates within the 0–40 cm layer over three years for all treatments combined. *** Significant at the 0.001 probability level. ** Significant at the 0.01 probability level. * Significant at the 0.05 level.

The relationship between SOC sequestration (bulk soil) and annual average C input was expressed by the following equation: y = 0.413x − 0.249, y = ΔSOC, x = annual average C input (Mg ha^{-1} y^{-1}). The slope (0.413) indicates the sequestrated portion of the C input. This equation indicated that an annual C input of 0.60 Mg ha^{-1} was required to maintain the initial SOC level at this site, i.e., y = 0. Soil C stock in the >2 mm and 0.25–2 mm aggregates was positively correlated with the annual average C input ($p < 0.01$). The soil C stock in the 0.053–0.25 mm aggregate decreased with the increasing annual average C input, but this decrease was not significant.

The slopes of the linear relationship between annual average C input and C stock in >2 mm, 0.25–2 mm, and 0.053–0.25 mm aggregates were 1.06, 1.67, and −0.50, respectively (Figure 5). The carbon conversion rate of the 0.25–2 mm aggregate was 1.59 and 3.34 times higher than that of the >2 mm and 0.053–0.25 mm aggregates, respectively, which indicated that the increased organic carbon was mainly sequestered in 0.25–2 mm aggregates.

3.6. Correlation and PCA

The correlation analysis showed that BD was negatively correlated with the proportion of >2 mm and 0.25–2 mm aggregates, CSA1, CSA2, and CSA3 and SSA1, SSA2, and SBS (r ranged from −0.43 to −0.69; $p < 0.05$) (Figure 6). SBS was significantly and positively correlated with CSA1, CSA2, CSA3, SSA1, SSA2, and porosity ($p < 0.05$).

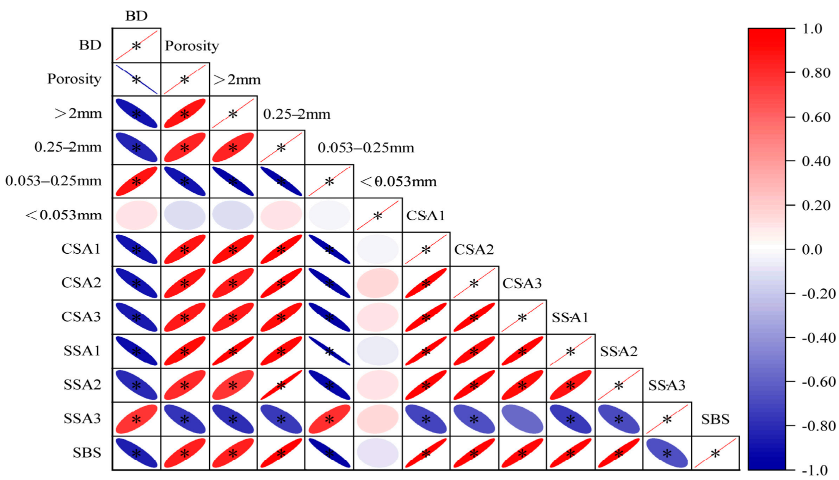

Figure 6. Correlation between soil properties as influenced by maize straw and bentonite soil amendments. * Significant at the 0.05 level. Note: >2 mm, 0.25–2 mm, 0.053–0.25 mm, and <0.053 mm, the mass proportions of aggregates from large to small; CSA1, CSA2, and CSA3, organic carbon concentration of aggregates from large to small particle sizes; SSA1, SSA2, and SSA3, organic carbon stock of aggregates from large to small particle sizes; SBS, SOC stock of bulk soil.

To further assess the relationship among soil properties, PCA was performed on the data. Soil properties varied considerably among the four treatments, as indicated by different locations on the PCA biplot (Figure 7). The components of PC1 and PC2 accounted for 96.9% of the total variance in soil properties, and 91.89% of this variance was explained by PC1, while another 5.01% was explained by PC2. The different treatments were well-separated along the PC1 axis (Figure 7). The T1, T2, and T3 treatments were on the left side while the CK treatment was on the right side, representing the difference in soil quality imparted by the amendment treatments compared to CK.

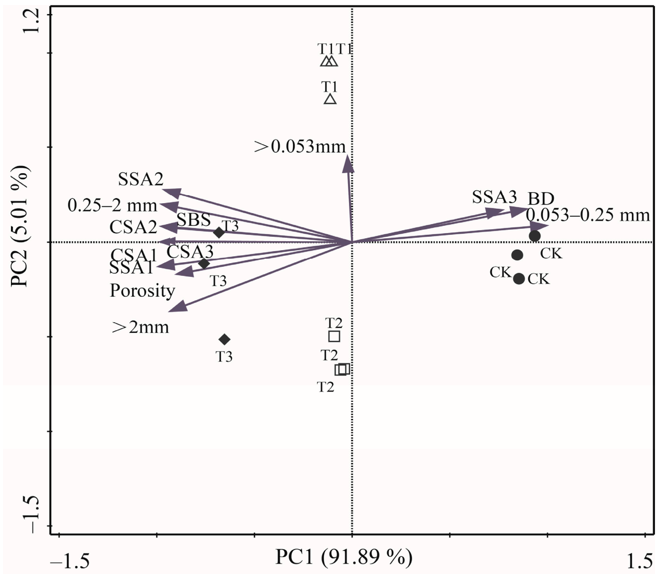

Figure 7. Principal component analysis (PCA) scores (PC1 and PC2) for soil properties as influenced by maize straw and bentonite soil amendments.

4. Discussion

4.1. Effect of Maize Straw Combined with Bentonite on Soil Bulk Density and Porosity

Soil bulk density affects crop production and soil quality, and it has been used as an indicator of soil structure. Our study showed that the application of maize straw and bentonite treatments reduced soil bulk density and improved porosity in the 0–40 cm soil layer compared to CK (Figure 1). This was similar to the results of Zhou et al. [34], who found that soil bulk density decreased by 6–10% in the 0–40 cm layer over seven years with bentonite–humic acid applied to sandy soil. Fan et al. [15] analyzed the response of soil bulk density to straw addition and found that soil bulk density was decreased by 2–27% in 0–20 cm. Generally, soil amendments can alter the soil's physical and structural properties, and these effects occur directly through the inherent material properties and indirectly by promoting biological activity, as well as promoting the growth of roots and mycelia associated with inputs of organic matter [43,44]. Bentonite belongs to the 2:1 clay family, and this family of clay minerals has the "shrink-swell" properties, which leads to a change in soil volume accompanying a change in soil moisture content [45]. Straw, as an exogenous organic material, has a high cellulose content, low bulk density, and large specific surface area, which can effectively loosen the soil and reduce soil bulk density and promote an increase in soil porosity after addition to the soil [15]. In addition, the chemical conditions created by the secretion of organic acids by roots, microorganisms, and organic matter decomposition also promote the fracturing of the soil conglomerate, which eventually leads to a decrease in soil bulk density and the improvement of porosity [46]. We also found that soil bulk density was lowered further with the addition of bentonite combined with the maize straw as it improved the aggregation status; the two amendments complement each other. In our study, larger changes in soil bulk and porosity were observed in the 20–40 cm depth layer rather than in the 0–20 cm depth layer; this might be due to a combination of differences in the vertical distribution of the straw and bentonite and the distribution of roots of the oat crop. In addition, our results indicated that soil bulk density showed a negative correlation with >0.25 mm aggregates and their associated organic carbon concentration and SOC stock. Coarse structure is one of the most important factors limiting SOC stabilization in sandy soils [19]. This was consistent with previous research, which found that fine-textured soils had high SOC [47]. A decrease in soil bulk density would cause an increase in SOC and porosity, consequently increasing soil infiltration and water and air storage capacities [48].

4.2. Effect of Maize Straw Combined with Bentonite on C Input and ΔSOC

A survey report on soil organic carbon recognized that the Loess Plateau is one of the ecologically fragile zones of northern China with the lowest SOC density values; therefore, restoration practices should be strengthened in these areas [47]. In our study, maize straw combined with bentonite treatment exhibited the highest ΔSOC. Changes in C inputs (e.g., straw, bentonite carbon, root, stubble, and rhizodeposition) under different farmland management practices may induce variations in soil C stocks. C inputs increased under maize straw combined with bentonite, and ΔSOC increased accordingly (Table 1). This result is supported by Vidal et al.'s [49] viewpoint that the addition of the montmorillonite mineral additive with organic amendments might promote plant-derived OC transfer to the soil and thus enhance soil C stocks in the longer term. Similarly, Karbout et al. (2021) [50] observed high SOC stock (2862 ± 3.4 g m^{-2}) in oasis soil amended with bentonite clay combined with organic amendments (manure and compost) in the Fatnassa oasis in Tunisia. In the present study, the SOC sequestration efficiency in the maize straw combined with bentonite treatment was higher than that of other treatments. This difference was likely caused by the quantity and quality of C input, i.e., different supply sources of C. The addition of C via exogenous materials (maize straw and bentonite) facilitated SOC sequestration, and sequestration efficiency increased with an increase in C input [51]. This was accompanied by increased microbial activity and the release of nutrients. In addition, the enhanced formation and stability of aggregates helped protect the SOC that was already sequestered [52]. Moreover, the positive linear relationship observed between the annual average C input and ΔSOC (Table 2 and Figure 5) indicated that sandy soils in arid areas in the Loess Plateau had the potential for additional C sequestration. Bentonite and straw are abundant in China [53,54], and China also has large sandy soil areas in semi-arid regions in need of amelioration [34]. The addition of the maize straw combined with bentonite soil amendment appears to be a promising practice to improve sandy soil C sequestration and soil health.

4.3. Effect of Maize Straw Combined with Bentonite on the Distribution, SOC Concentration, and C Stock of Soil Aggregates

Aggregates are key to SOC stabilization, but the durability of aggregates is sensitive to agricultural management practices [55]. In our study, the 0.053–0.25 mm aggregates under different treatments were significantly higher than >0.25 mm aggregates (Figure 2). This phenomenon in our study might be influenced by soil texture. Niu's [56] study showed that clay minerals are the main cementing substances for sandy soils to form aggregates. In the dryland farming areas of the Loess Plateau, the soil structure is loose, the sand content is high, the cohesion between particles is low, and it is not easy to form large aggregates [57,58]. In this work, maize straw combined with bentonite treatment changed the distribution of soil aggregates, increasing the proportion of >2 mm and 0.25–2 mm aggregates and decreasing the portion of 0.053–0.25 mm aggregates. This indicated that the application of maize straw combined with bentonite was conducive to the formation of larger aggregates and could effectively improve the structure of sandy soil and improve soil health. The higher proportion of >2 mm and 0.25–2 mm aggregates under this practice may be attributed to organic matter conservation under the bentonite and the formation of organic–mineral complexes in the soil [59]. The soil amendments increase soil binding agents (i.e., roots, fungal hyphae, polysaccharides, and clay) [10,16,60], which is conducive to the development of soil pores and the formation of soil aggregates and effectively improves the soil's structure, thereby enhancing the physical, chemical, and biological protection of organic carbon by aggregates.

Findings from this study point to significant differences in the distribution of SOC in different aggregate sizes (Figure 3). The concentrations of SOC in aggregates >0.25 mm were higher than those in 0.053–0.25 mm aggregate. This is evidenced by the aggregate hierarchical development model theory proposed by Tisdall and Oades [61], which conjectures that aggregates are formed sequentially, i.e., microaggregates are first formed free and then are bound together into macroaggregates (>0.25 mm) by binding agents. The theory also indicates that the C concentration in large aggregates of >0.25 mm is most responsive to the addition of exogenous materials; this has also been confirmed in our analysis (Figure 5). The higher C stock associated with 0.053–0.25 mm aggregate could be explained by the relatively high mass percentage of this aggregate size (Figure 2). In particular, maize straw combined with bentonite treatment also had a greater effect on the C concentration and stock of >0.25 mm soil aggregates compared to other treatments. Studies by Niu et al. [56] and Mustafa et al. [62] showed that in the absence of exogenous C input and low clay content, soil organic matter formation is a relatively slow process, especially in sandy soils. The application of maize straw combined with bentonite addressed both issues simultaneously in sandy soil areas [63,64]. This was evidenced by the combined amendments with significantly higher C inputs promoting the formation of aggregates (Figure 2, Table 2), Moreover, it was found that there was a significant positive correlation between annual average C input and C stock of >0.25 mm aggregates (Figure 5). Another important factor is that increased soil-binding agents (i.e., roots, fungal hyphae, polysaccharides, and clay) [10,16,59,65] promote the formation of aggregates, which impede the decomposition of organic matter through physical protection [66]. Moreover, there was a positive relationship between SOC stock of bulk soil and SOC stock of >0.25 mm aggregates (Figures 6 and 7), indicating that the larger aggregate sizes still have a relatively greater potential to sequester C, which further emphasizes the significance of promoting >0.25 mm aggregates for carbon sequestration.

5. Conclusions

Maize straw combined with bentonite had obvious soil structure improvement and organic carbon sequestration effects. Decreased soil bulk density and increased soil porosity and proportions of >0.25 mm aggregates provided physical protection of SOC and enhanced SOC concentration and SOC stock of bulk soil. Significant linear relationships among annual average C input, ΔSOC of bulk soil, and C stocks of the different sizes of aggregates were observed, and the correlation coefficients of 0.25–2 mm aggregates were the largest, indicating that the carbon sequestration potential of dryland farming in the Loess Plateau in China is still great. Added C was primarily sequestered in aggregates of 0.25–2 mm. Therefore, this suggests that maize straw (6 Mg ha^{-1}) combined with bentonite (18 Mg ha^{-1}) is a feasible and practical strategy to improve sandy soil quality in the Loess Plateau in China or other sandy soils in a similar climate. Further investigations should consider using the tracer technology to accurately estimate the input and turnover of C in bulk soil and aggregates and the long-term effect on SOC sequestration, microorganism activity, crop yield, and economic benefits.

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