Optimization of tillage rotation and fertilization increases the soil organic carbon pools and crop yields in a wheat-maize cropping system on China's Loess Plateau

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Abstract

Long-term application of high nitrogen and phosphorus fertilizer and mono-tillage practices can adversely affect soil health, carbon sequestration and crop growth. A 10-year field experiment was conducted in a wheat-maize cropping system on the Loess Plateau in China to explore fertilization and tillage methods that improve SOC sequestration and crop yields. We evaluated the effects of (1) fertilization (balanced fertilization (BF), low fertilization (LF), and conventional fertilization (CF)) and (2) alternating years of different tillage (no-tillage and subsoiling (NS), subsoiling and ploughing (SP), ploughing and no-tillage (PN)) or continuous ploughing tillage (PP) on input-C, SOC pool, and crop yields. BF and rotational tillage (NS, SP, and PN) increased the amount and stabilization rate of input-C, thereby increased SOC storage, and the highest effect was found in BF+NS treatment. Simultaneously, BF produced higher contents of SOC, readily oxidizable carbon (ROC), particulate organic carbon (POC) and dissolved organic carbon (DOC) and C pool management index (CMI) at 0-10 cm depth. For tillage, rotational tillage increased labile C contents and CMI at 0-10 cm, 20-35 cm and 35-50 cm depths, which improved soil quality. Crop yields showed an increase tendency with the increases of SOC content, labile C fraction contents, and CMI. Therefore, the higher yields of wheat and maize were found in BF and rotational tillage; the highest were in BF+NS treatment. Our finding suggested that NS combined with BF may be the best management to increase SOC storage, improve soil quality and productivity on China's Loess Plateau.

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ABSTRACT: Long-term application of high nitrogen and phosphorus fertilizer and mono-tillage practices can adversely affect soil health, carbon sequestration and crop growth. A 10-year field experiment was conducted in a wheat-maize cropping system on the Loess Plateau in China to explore fertilization and tillage methods that improve SOC sequestration and crop yields. We evaluated the effects of (1) fertilization (balanced fertilization (BF), low fertilization (LF), and conventional fertilization (CF)) and (2) alternating years of different tillage (no-tillage and subsoiling (NS), subsoiling and ploughing (SP), ploughing and no-tillage (PN)) or continuous ploughing tillage (PP) on input-C, SOC pool, and crop yields. BF and rotational tillage (NS, SP, and PN) increased the amount and stabilization rate of input-C, thereby increased SOC storage, and the highest effect was found in BF+NS treatment. Simultaneously, BF produced higher contents of SOC, readily oxidizable carbon (ROC), particulate organic carbon (POC) and dissolved organic carbon (DOC) and C pool management index (CMI) at 0-10 cm depth. For tillage, rotational tillage increased labile C contents and CMI at 0-10 cm, 20-35 cm and 35-50 cm depths, which improved soil quality. Crop yields showed an increase tendency with the increases of SOC content, labile C fraction contents, and CMI. Therefore, the higher yields of wheat and maize were found in BF and rotational tillage; the highest were in BF+NS treatment. Our finding suggested that NS combined with BF may be the best management to increase SOC storage, improve soil quality and productivity on China's Loess Plateau.

KEYWORDS: rotational tillage; fertilization; soil organic carbon sequestration; organic carbon fractions; crop yields.

1. INTRODUCTION

Soil organic carbon (SOC) is not only a major indicator to evaluate soil fertility, but also a primary pool of global carbon storage (about 1580 Gt C) (Schimel, 1995). Efforts to increase SOC content are thought to significantly reduce atmospheric CO_2 and enhance soil fertility and crop productivity (Sauerbeck, 2001). Soil tillage is one of the main human factors to cause the changes in the SOC pool. Long-term conventional tillage (CT) decreased labile C content (Cheng et al., 2012) and caused 25-75% SOC mineralization loss (Nicoloso et al., 2018). Meanwhile, conservation tillage reportedly increase the labile C contents and SOC sequestration (Somasundaram et al., 2016; Badagliacca et al., 2018). The influence of tillage is dependent on tillage depth. Carbonell et al. (2015) observed that the positive impacts of NT on SOC and labile C were limited to the topsoil (0-10 cm). The influence of tillage method on the SOC pool also is dependent on soil type and environmental factors. Also, different tillage practices significantly influence crop yields. Previous researchers found that NT and minimum tillage increase SOC sequestration and crop yields (Sun et al., 2018a; Márcio et al., 2018) and that subsoiling tillage (ST) could enhance root growth and improve crop yields (Sun et al., 2018b). However, other studies suggested that long-term mono-conservation tillage was noneffective to improve crop productivity (Stewart et al., 2017; Li et al., 2018) and some even found that NT negatively affected crop yields compared with CT (Zhao et al., 2017; Bogunovic et al., 2018). Therefore, the influences of single continuous conservational tillage on crop yields are unclear. Recent studies have reported that rotational tillage effectively prevented the disadvantages of mono-tillage, while increasing SOC content and crop productivity (Chu et al., 2016; Wang et al., 2018). Nevertheless, the data about the impacts of tillage rotation systems on SOC sequestration, labile C content, soil quality, and crop productivity on the China's Loess Plateau is lacking.

Fertilization is an indispensable agricultural practice used to achieve high yields, and it also changes SOC content. Previous studies have indicated that inorganic fertilizer application significantly improved crop productivity and increased crop residues amount returned to the field and therefore increased SOC and labile C contents (Nayak et al., 2012; Ghimire et al., 2017). A study reported by Chaudhary et al. (2017) indicated that soils fertilized over the long term contained higher levels of SOC, readily oxidizable C (ROC), particulate organic C (POC), and dissolved organic C (DOC) than unfertilized soils. Some studies have indicated that the positive influences of fertilization on crop yields only occur with balanced fertilization and not with unbalanced fertilization (Kukal et al., 2009; Shahid et al., 2017). Whereas, Liang et al. (2012) observed that inorganic fertilizer application has no significant positive effects on SOC, labile C, and crop yields. These inconsistent results may be related to climate, soil type, crop system, experimental duration, and other factors (Samuel et al., 2018). Therefore, studies of the impacts of fertilization on SOC sequestration and crop growth should be accordance with local conditions.

The Loess Plateau is located in Northwest China and is a major production region for wheat and maize (Ren et al., 2016). Long-term intensive conventional tillage system has caused a series of troubles, such as increased soil erosion, loss of SOC due to mineralization, and degradation in soil quality (Chen et al., 2009). Therefore, conservational and rotational tillage practices with crop straw return have been viewed as potential options. Loess soil fertility is low because of low contents of SOM, total nitrogen (N), and available phosphorus (P), whereas total potassium (K) content is high due to the rich illite minerals in soil parent material (De et al., 2011). Thus, to pursue short-term high crop yields, farmers have always adopted a fertilizing mode of high N and P in this region, which is not conducive to sustainable soil production. Recently, some studies have shown that the balanced application of N, P, and K fertilization can strongly improve crop productivity (Lu et al., 2017). On the whole, to find the optimal mode of fertilization and tillage for the Northwest China region, it is essential to assess the impacts of fertilization and rotational tillage on SOC sequestration, soil quality and crop productivity in this region.

In this study, our objectives were to study the changes of SOC sequestration, soil labile C fractions, C pool management index (CMI), and crop yields under different fertilization and tillage methods. Thus, a 10-year (2007 to 2016) field experiment with different fertilization and tillage modes in a wheat-maize crop system in the Loess Plateau was established to test the following hypotheses: (i) balanced application of N, P, K fertilization with the rotation of different tillage practices would increase wheat and maize yields and increase the SOC stock by increasing the amount of crop residues returned to the field and (ii) annual rotation of no-tillage and subsoiling would increase the SOC content and soil labile C fractions, thus improving the CMI and crop productivity in the China's Loess Plateau.

2 | MATERIALS AND METHODS

2.1 | Site

This work was conducted over ten years (2007 to 2016) in the Dryland Agricultural Research Station of Northwest A & F University, located in Heyang County (104deg04'E, 35deg19'N altitude 877 m), Shaanxi Province of Northwest China. The climate at the research station is temperate semi-arid continental monsoon. In this region, the mean annual frost-free period is 210 days. The annual mean precipitation, evaporation and temperature were 536.6 mm, 1,833 mm and 11.5 degC, respectively. The soil in this region is classified as a Chromic Cambisol (sand 34%, silt 39%, clay 27%) using the FAO/UNESCO Soil Classification (1993). The main soil characteristics (0-50 cm) at the beginning of study are listed in Table S1.

2.2 | Experimental design

We adopted a plit-plot design for this experiment. Fertilization treatment was kept in primary plot treatment and included: balanced fertilization (BF), low fertilization (LF), and conventional fertilization (CF). Tillage method was the sub-plot treatment and included: no-tillage rotated with subsoiling in alternating years (NS), subsoiling rotated with ploughing in alternating years (SP), ploughing rotated with no-tillage in alternating years (PN), and ploughing applied every year (PP). Five complete cycles of rotations were implemented during the ten years (2007 to 2016). The two factors were combined into 12 treatments.

Fertilization treatment: BF, N: 150 kg ha^{-1}, P_2O_5: 120 kg ha^{-1}, and K_2O: 90 kg ha^{-1}; LF, N: 75 kg ha^{-1}, P_2O_5: 60 kg ha^{-1}, and K_2O: 45 kg ha^{-1}; CF, N: 225 kg ha^{-1}, P_2O_5: 180 kg ha^{-1}, and no potassium fertilizer applied. Wheat and maize had the same amount of fertilizer application under the same fertilization treatment. The N, P_2O_5, and K_2O were from urea (N: 46.4%), diammonium phosphate (N: 18%, P_2O_5: 44%), and potassium chloride (K_2O: 60%), respectively. The full rates of P and K plus 50% of N was applied on the sowing date for maize, the remaining 50% of N was used at the 12th leaf stage (the middle of June each year). The full rates of N, P, and K fertilizers were used once on the planting date for wheat.

Tillage methods: In no-tillage (N), crop residue was chopped and covered on the topsoil, the soil was left undisturbed until sowing. In subsoiling (S), sub-soiling, the crop residue was chopped and covered on the topsoil. The topsoil remained undisturbed while the subsoil was subsoiled (30-35 cm depth, 60 cm width) using a subsoiler. In ploughing (P), the crop residue was chopped, and mixed with the soil (20-25 cm depth) using a moldboard plow. Fields were tilled according to the described methods after crop harvest each year.

Planting: The winter wheat/spring maize rotation system was carried out in this study. For winter wheat (cultivars: Jinmai 47 before 2014, Chang 6359 after 2014), the time of planting and harvesting were in the end of September and early June of the following year, respectively. The seeding rate and row spacing were 150 kg ha^{-1} and 20 cm, respectively. For spring maize (cultivars: Yuyu 22 before 2014, Zhengdan 958 after 2014), the time of planting and harvesting were in April and the end of September, respectively. The seeding rate and row spacing were 37.5 kg ha^{-1} and 60 cm, respectively. Table S2 describes the crop rotation schedule from 2007 to 2016.

2.3 | Soil sampling and processing

Soils were randomly sampled in 0-10 cm, 10-20 cm, 20-35 cm and 35-50 cm layers with three replications under different treatments in June 2016 after winter wheat harvest. After air-drying, samples were ground and sieved to 0.25-mm for analyzing the soil C fractions. SOC was obtained with the K_2CrO_7-H_2SO_4digestion method (Walkley and Black, 1934). Readily oxidizable C (ROC) was measured using the 333 mmol L^{-1} $KMnO_4$ oxidation method described by Blair et al. (1995). Dissolved organic C (DOC) was determined as described by Jiang et al. (2006). The $CHCl_3$ fumigation-extraction method was used to measure Microbial biomass C (MBC) (Vance et al., 1987). Particulate organic C (POC) was measured according to the description of Cambardella and Elliott (1992).

Total SOC stock was calculated as

$\mathrm{SOC}_{\mathrm{stock}} = 0.1 \times \mathrm{SOC}_c \times D \times T(1)$

Where $\mathrm{SOC}_{\mathrm{stock}}$ (Mg ha^{-1}) is the stock of SOC, SOC_c (g/kg) is SOC content, D (g cm^{-3}) and T (cm) represent soil bulk density and soil thickness, respectively.

$\Delta\Sigma\mathrm{O\hat{}}_{\mathrm{stock}} = \mathrm{SOC}_{\mathrm{stock}} - \mathrm{SOC}_{stock0}(2)$

Where$\Delta\Sigma\mathrm{O\hat{}}_{\mathrm{stock}}$ (Mg/ha) is the SOC stock accumulation and SOC_{stock0}(g kg^{-1}) is the SOC stock before the experiment.

CMI was calculated according to the description of Blair et al. (1995). The CF+PP treatment is the reference in the equation:

$L = \mathrm{ROC}_c/\mathrm{SOC}_c$ (3)

Where L is the lability of SOC, ROC_c is the content of readily oxidized carbon, and SOC_c (g kg^{-1}) is SOC content.

$\mathrm{CPI} = \mathrm{SOC}_{\mathrm{cs}}/\mathrm{SOC}_{\mathrm{cr}}$ (4)

Where*CPI*stands for carbon pool index, $\mathrm{SOC}_{\mathrm{cs}}$ and$\mathrm{SOC}_{\mathrm{cr}}$ (g/kg) are the soil organic carbon content of the sample and the reference (CF+PP treatment), respectively.

$\mathrm{LI} = L_C/L_R$ (5)

Where LI is the C lability index, L_C and L_R stand for the C lability of the sample and the reference (CF+PP treatment).

$\mathrm{CMI} = \mathrm{CPI} \times \mathrm{LI} \times 100$ (6)

2.4 | Estimation of plant biomass carbon inputs

In each treatment, wheat and maize samples were randomly collected from three 3 m^2 and three 9 m^2 areas at the harvest period. After air-drying, the samples were manually threshed and weighed to determine the yields and straw amount.

The input-C from straw, C_{straw}, was calculated as:

$C_{\text{straw}} = B_{\text{straw}} \times 0.40$ (7)

Where B_{straw} is crop straw biomass, plant biomass C input was calculated by assuming that C content in plant tissue is 40% according to the study of Johnson et al. (2006).

The input-C from crop stubble, C_{stubble}, was calculated as:

$C_{\text{stubble}} = B_{\text{straw}} \times r \times 0.40$ (8)

Where r is the stubble to straw ratio. For Maize, stubble represented 10% of straw biomass. For wheat, stubble represented 20% of straw biomass (Li et al., 2016).

The input-C from roots, C_{root}, was calculated as:

$C_{\text{root}} = B_{\text{straw}} \times r \times 0.40$ (9)

Where$r$ is the root to straw ratio. Root represented 23% (maize) and 22% (wheat) of straw biomass according to the description of Kong et al. (2005).

The input-C from rhizodeposition (C_{rhizodep}) was calculated as follows (Maillard et al., 2018):

$C_{\text{rhizodep}} = C_{\text{root}} \times 0.65$ (10)

The stabilization rate (SR, %) of plant biomass carbon into SOC at the 0-50 cm depth was assessed as follows (Srinivasarao et al., 2012):

$SR = \Delta\Sigma O\check{}_{\text{stock}}/C_{\text{input}}$ (11)

Where$C_{\text{input}}$is accumulative plant biomass C input.

2.5 | Statistical analysis

SAS 9.0 (SAS Systems, Cary, NC, USA) was used for data analysis. Origin 2016 was used for graphing. The Split-plot analysis of variance (ANOVA) was applied to assess the impacts of fertilization and tillage on input-C, SOC, soil labile C fractions (including ROC, DOC, MBC and POC), CMI and crop yields. The multiple comparisons were conducted on the basis of the Duncan Multiple Range Test (at < 0.05 level). And the relationships among the indexes were evaluated by regression equations.

3 RESULTS

3.1 | Accumulative plant biomass C input

The cumulative C input from crop residue (including crop straw, crop roots and rhizodeposition) in the 10-year experimental period (2007-2016) are shown in Table S3 and Figure 1. The fertilization treatments caused significant differences in the accumulative plant biomass C input, and the total C input under BF higher than that under LF and CF. Simultaneously, rotational tillage systems (SP, PN, and NS) significantly increased the C inputs from straw, root residue, stubble, and rhizodeposition. Compared with the PP, total C input were 18.10%, 11.04% and 14.72% higher in the SP, PN, and NS tillage than that in PP, respectively.

3.2 | SOC

The effects of the fertilization on SOC content at 0-20 cm depth were significant after ten years, but were not significant in the deeper layers (Figure 2, $p < 0.05$). Compared with the CF, the BF and LF significant increased the SOC content and stocks at the 0-10 cm and 10-20 cm depth. At the 0-50 depth, SOC stock under different fertilization treatments was followed by BF > CF > LF, and the statistical differences were found among three fertilization treatments (Table S4; Figure 3; $p < 0.05$). Significant effects on SOC content and stocks due to tillage system were detected at the 0-50 cm depth ($p < 0.05$). SOC stock was markedly higher in the rotational tillage (SP, PN, and NS) than that in PP tillage. More specifically, compared with PP tillage, the NS, SP, and PN tillage primarily increased SOC content and stocks at the 0-10 cm depth. Similarly, the rotational tillage systems also increased SOC content in $>$ 10 cm soil layers. The difference was significant between NS and PP in10-20 cm and 35-50 cm layers, was significant between SP and PP in the 20-35 cm and 35-50cm layers, and was significant between PN and PP at the 20-35 cm depth ($p < 0.05$).

The SOC stocks of all treatments increased after the ten-year experiment, and the maximum increment by 6.83 Mg ha^{-1} was in the treatment of BF+NS, the minimum increment by 2.54 Mg ha^{-1} was in the treatment of CF+PP (Figure 3). The SOC stock accumulation at the 0-50 depth was higher under BF and LF than that under CF, and there was a statistical difference between BF and CF ($p < 0.05$). Changes in SOC stock accumulation under different tillage systems decreased in the order of NS $>$ PN $>$ SP$>$ PP, and the statistical differences were found between rotational tillage and PP tillage ($p < 0.05$).

3.3 | Stabilization rate

The proportion of SOC stock accumulation to total C input is the stabilization rate (Figure 4). The stabilization rate in the treatment of BF+NS was 17.08%, which was the highest among all treatments. The lowest stabilization rate was recorded (7.66%) in the CF+PP treatment. For fertilization effect, the stabilization rate were increased by 39.00% in BF and by 33.79% in LF compared with CF. Meanwhile, the effect of tillage on the stabilization rate was significant. Compared with the PP, the stabilization rate were significantly increased by 61.54%, 20.83%, and 26.92% in the NS, SP, and PN, respectively (p <0.05).

Figure 5 showed that SOC stock accumulation was positively correlated with total C input, and the stabilization rate of plant biomass C (p <0.05).

3.4 | Soil labile C fractions

Table 1 showed the differences of soil labile C fractions (ROC, DOC, MBC, and POC) among treatments (p $<$ 0.05). For fertilization effect, the order of ROC content under different fertilization treatments was BF $>$ CF $>$ LF in the topsoil (0-10 cm), and there were statistical differences between BF and LF ($p < 0.05$). However, the differences in ROC content among the three fertilization treatments were nonsignificant at $>$ 10 cm depth. Tillage had significant effects on ROC in all soil layers (0-50 cm). Compared with PP tillage, NS and SP significantly increased ROC content at the 0-10 cm, 20-35 cm, and 35-50 cm depth; and PN significantly increased ROC content at the 0-10 cm and 20-35 cm depth ($p < 0.05$).

Significant effects of the fertilization treatments or tillage systems on DOC content were detected in all soil layers (0-50 cm) (Table 1). DOC content with BF was higher than that with CF at the 0-10 cm, 10-20 cm, and 20-35 cm depth, and DOC content was lower with LF than that with CF at the 0-10 cm and 35-50 cm depth ($p < 0.05$). For tillage effect, DOC content was significantly higher in rotational tillage systems (NS, SP, PN) than that in PP tillage in all soil layers (0-50 cm)(P <0.05). More specifically, compared with PP, DOC content increased by 40.92%, 10.89%, 15.64%, 30.95% under NS, increased by 13.56%, 5.03%, 8.00%, 20.48% under SP and increased by 24.94%, 12.29%, 10.55%, 13.33% under PN at 0-10 cm, 10-20 cm, 20-35 cm and 35-50 cm depth, respectively.

The content of MBC was followed by CF $>$ BF $>$ LF in all layers (0-50 cm), and there were statistical differences between LF and CF (Table 1). Tillage method affected MBC content in all layers (0-50 cm). Compared with PP tillage, rotational tillage systems (NS, SP and PN) significantly increased MBC content at the 0-10 cm, 20-35 cm, and 35-50 cm depth. Meanwhile, NS, SP and PN decreased MBC content compared to PP tillage at 10-20 cm depth ($p < 0.05$).

Fertilization treatment markedly affected POC content at the 0-10 cm and 10-20 cm depth, and POC content was higher with the BF treatment than that with the CF and LF treatments (Table 1). Tillage significantly affected POC content. Compared with PP, POC content increased by 58.79%, 15.73%, 67.39% under NS, increased by 26.06%, 41.57%, 36.96% under SP and increased by 42.42%, 28.09%, 30.43% under PN at 0-10 cm, 10-20 cm and 35-50 cm depths, respectively.

3.5 | Carbon pool management index

After ten years, the SOC lability (L) and SOC lability index (LI) of the 0-10 cm and 35-50 cm depths were higher under CF treatment than those under BF or LF treatment, whereas the C pool index (CPI) of the topsoil (0-10 cm) was lower under CF than that under BF and LF and CMI of the 0-10 cm and 10-20 cm depths were greater under BF than those under LF and CF (Table 2). For tillage effect, the L and LI at the 0-10 cm and 20-35 cm depths under rotational tillage systems (NS, SP, and PN) were higher than those under PP tillage ($p < 0.05$). And compared with PP, rotational tillage systems significantly increased CPI at the 0-10 cm and 10-20 cm depths ($p < 0.05$). Meanwhile, CMI was higher under rotational tillage systems (NS, SP and PN) than that under PP tillage at the 0-10 cm, and 20-35 cm depths. Moreover, NS and SP also strongly increased CMI in the 35-50 cm soil layer ($p < 0.05$).

3.6 | Crop yields

The wheat and maize yields from 2008 to 2016 were strongly affected by fertilization treatments and tillage systems (Table S5 and Figure 6). For fertilization effect, the yield of wheat and maize were both followed by BF > CF > LF. Compared with LF, the yields with BF were significantly increased by 11.70% for wheat on average and 8.31% for maize in average ($p < 0.05$). For tillage effect, rotational tillage systems (NS, SP and PN) produced higher wheat and maize yields than the PP tillage. More specifically, compared with PP, wheat yields on average were increased by 12.71%, 8.89%, and 12.83% in NS, SP, and PN, maize yields in average were increased by 14.05%, 8.83%, and 12.59% in NS, SP, and PN, respectively. On the whole, the minimum average yield of wheat and maize were found in LF+PP treatment, the maximum average yield of wheat and maize were found in BF+NS treatment.

Regression analysis showed the positive relationships were found between crop (wheat and maize) yields and SOC and it's labile fractions (Figure 7). The correlation coefficients of crop yields (wheat yield, maize yield) and SOC were smaller than the correlation coefficients of crop yields and soil labile C fractions (ROC, MBC, DOC and POC), indicating that the positive influences of labile C fractions on crop yields were more significant than those of SOC. Wheat and maize yields were positively correlated with CMI.

4 | DISCUSSION

4.1 | Impacts of long-term tillage rotation and fertilization on SOC content and SOC stocks

In this study, fertilization and tillage significantly affected SOC content and stock, whereas their interaction was slight. The SOC stock under BF was markedly greater than that under CF and LF at the 0-50 cm depth. This was primarily since balanced fertilization was beneficial to crop growth and increased the amount of returned crop residues. Compared to CF, BF and LF reduced the application amount of nitrogen and phosphate fertilizer. Lu et al. (2011) indicated that excessive application of N fertilizer might reduce the ratio of C: N in soil, accelerated decomposition of crop straw by soil microorganisms, result in the lower carbon sequestration. In other words, the increase of SOC is more related to the stabilization rate of input C, which also was confirmed by that the linear correlation coefficient between SOC storage and the stabilization rate (0.96) was higher than that between SOC storage and input C (0.55) (Figure 5). In our study, BF and LF increased in SOC contents at the 0-10 cm and 10-20 cm depth due to the higher stabilization rate of input C. In addition, N and P nutrients enriched by long-term high rates of fertilizers could accelerate the decomposition of SOC (Luo et al., 2019), which may be one reason to explain the SOC content in CF lower than in BF and LF.

At the end of the ten-year experiment, the higher levels of SOC stocks were found at the 0-50 cm depth under rotational tillage systems (NS, SP, and PN) than under PP. That can be related to the higher plant biomass C input under rotational tillage systems (Figure 1) and the lower mineralization of SOC. Previous studies reported that conservational tillage, such as no tillage, could reduce soil disturbance, decreases the mineralization rate of SOC and promote the accumulation and humification of crop residues returned to the soil (Mazzoncini et al., 2013). Based on the observed SOC changes in different soil layers, the rotational tillage systems (NS, SP, and PN) increased the SOC content and SOC stock accumulation of the 0-10 cm depth compared to PP. The reason for this difference is that rotational tillage causes less soil disturbance, which allows the returned crop residues to cover most of the soil surface (He et al., 2019). The rotational tillage systems also increased SOC content in > 10 cm layers, and the effect of NS at 10-20 cm and 35-50 cm depths was obvious. This can be attributed to two factors: (1) The rotational tillage systems increased the incorporation of crop residues by input at depth where there may be a greater chance of protecting SOC by the combination with the mineral matrix (Hou et al., 2012); (2) subsoil tillage can break the bottom layer of the plow pan and promote crop root growth, which increases the production of root residues and secretions (Leonard et al., 2012). Poeplau and Don (2013) suggested that subsoil tillage can increase the production of crop root exudates and root litter and therefore increase the amount of SOM in the subsoil.

4.2 | Impacts of long-term tillage rotation and fertilization on soil labile C fractions and CMI

In our report, the ROC, DOC, and POC contents under the BF were higher than those under the LF or CF at the 0-10 cm depth. This was primarily because of the higher C input in the BF. Simultaneously, BF also increased DOC at the 10-20 cm and 20-35 cm depth compared to LF and CF, due to the migration of DOC with soil moisture (Kaiser and Kalbitz, 2012). Increasing the application of nitrogen and phosphorus fertilizers can stimulate soil microbial activity and therefore increase MBC concentrations (Ghosh et al., 2018), and we came to a similar conclusion that the content of MBC in the all layers (0-50 cm) under BF and CF was higher than that under LF. Compared with PP, the rotational tillage systems (NS, SP, and PN) increased the content of soil labile C fractions (ROC, DOC, MBC and POC) in soil surface layer (0-10 cm) by creating an environment in which more crop residues covered on the soil surface. Crop residues provide substrates for soil microorganisms and promote the accumulation of soil labile C (Jharna et al., 2018). In contrast, PP tillage weakened the physical protection of SOC, exposed protected SOC to microbial decomposition, accelerated mineralization of active organic matter in newly turned topsoil, thus increasing the loss of soil labile C (Chen et al., 2009). The rotational tillage systems also increased the content of soil labile C fractions in deep soil (20-35 cm and 35-50 cm), which may be as a result of the increased amount of root debris and exudate returning to the soil (Hou et al., 2012).

In our study, fertilizer application had a significant impact on CMI at the 0-10 cm and 10-20 cm depths and tillage had a significant influence on CMI in all layers (0-50 cm) (Table 2). The positive linear correlation between CMI and carbon input was found in the present study, indicates that higher crop residue inputs caused higher CMI. Similar observations were reported by Chatterjee et al. (2018). The CMI at the 0-10 cm depth was lager with BF than that with CF; rotational tillage systems (NS, SP, and PN) increased CMI compared to PP tillage. These results suggested that soil fertility can be healthily developed by balanced fertilization or rotational tillage. The value of CMI depends on SOC content and activity (Blair et al., 1995), that is increasing organic carbon input or reducing SOC mineralization in BF and rotational tillage could cause higher SOM content and labile organic C, thereby resulting in higher CMI.

4.3 | Impacts of long-term tillage rotation and fertilization on crop yields

In this study, BF with appropriate reductions in N and P fertilizer rates and supplemental K fertilizer improved wheat and maize yields, which was confirmed by Yang et al., (2006). This suggested that optimal yields cannot be obtained in the Loess Plateau by the fertilization methods of applying high N and P fertilizer and no K fertilizer. For tillage, the rotational tillage systems (NS, SP, and PN) increased wheat and maize yields compared with PP tillage. This is because the tillage rotation systems can prevent the decline in SOC caused by long-term intensive tillage and enhance soil fertility (Bhattacharyya et al., 2012). Water shortage is another important factor restricting crop growth in the Loess Plateau. Tillage rotation can reduce soil water evaporation by covering a large of crop residue on soil surface (Yu et al., 2020). In addition, the higher SOC content produced by tillage rotation promotes water storage and water absorption by crop, thereby increasing crop yields (Manns and Berg, 2014).

In our study, crop yields were significantly positively correlated with SOC and soil labile C fractions (ROC, MBC, DOC, and POC) (Figure 7), indicating that the increased content and activity of SOC had a positive impact on crop production (Li et al., 2016). The correlation coefficients of crop yield and soil labile organic C fractions were greater than those of crop yield and SOC, suggesting that soil labile organic C contributes more significantly to increased crop yields. Therefore, agricultural practices that increase the active components of SOC are crucial for maintaining soil fertility and increasing crop yields.

5| CONCLUSIONS

Our results demonstrate that fertilization and tillage practices affect the SOC pool in China's Loess Plateau. Balanced fertilization (BF) and rotational tillage (NS, SP, and PN) significantly increased SOC stocks, and NS rotation combined with BF produced the highest SOC stock among all treatments. SOC stock accumulation was positively correlated with plant biomass C input and with the stabilization rate (SR) of returned plant biomass C, indicate that BF and rotational tillage had positive effects on SOC sequestration by the increases of input-C and it's stabilization rate. The SOC, ROC, DOC, and POC contents were greater under BF than those under CF at the 0-10 cm depth. Meanwhile, rotational tillage systems increased the soil labile C contents at the 0-10 cm, 20-35 cm and 35-50 cm depths. BF and rotational tillage also significantly improved the CMI and soil quality due to changes in the content and activity of SOC. In addition, fertilization and tillage practices affected SOC content, soil labile C content and CMI, which in turn affect crop yields. BF and rotational tillage were effective in increasing the yields of wheat and maize. The highest average yields of wheat (increased by 30.93%) and maize (increased by 20.39%) were found in BF+NS treatment. We found that NS tillage with a balanced application of nitrogen phosphorus and potassium fertilizers could increase SOC sequestration, improve soil quality, and increase maize and wheat yields in China's Loess Plateau.

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CONFLICT OF INTEREST STATEMENT

The authors declare that no conflicts of interest.

AUTHOR'S CONTRIBUTION STATEMENT

Xudong Wang, Xia Zhang and Afeng Zhang designed experiments; Xia Zhang, Sixu Lu and Chenguang Wang carried out experiments; Xia Zhang analyzed experimental results. Xudong Wang, Xia Zhang and Afeng Zhang wrote the manuscript.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

REFERENCES

Badagliacca G., Emilio Benítez., Amato G., 2018. Long-term no-tillage application increases soil organic carbon, nitrous oxide emissions and faba bean (Viciafaba L.) yields under rain-fed Mediterranean conditions. Sci Total Environ, 639:350-359. https://doi.org/10.1016/j.scitotenv.2018.05.157

Bhattacharyya R., Tuti M D., Kundu S., Bisht J K., 2012. Conservation Tillage Impacts on Soil Aggregation and Carbon Pools in a Sandy Clay Loam Soil of the Indian Himalayas. Soil Sci Soc Am J, 76(2):617. https://doi.org/10.2136/sssaj2011.0320

Blair G., Lefroy R., Lisle L., 1995. Soil carbon fractions based on their degree of oxidation, and the development of a carbon management index for agricultural systems. Aust J Agr Res, 46(7):1459. https://doi.org/10.1071/AR9951459

Bogunovic I., Pereira P., KisicI., Sajko K., Sraka M., 2018. Tillage management impacts on soil compaction, erosion and crop yield in Stagnosols (Croatia). CATENA, 160:376-384. https://doi.org/10.1016/j.catena.2017.10.009

Cambardella C A., Elliott E T., 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J, 56, 777-783. https://doi.org/10.2136/sssaj1992.03615995005600030017x

Carbonell-Bojollo R., González-Sánchez E J., Repullo Ruibérriz de Torres M., Ordóñez-Fernández R., DomÍnguez-Gimenez J., Basch G., 2015. Soil organic carbon fractions under conventional and no-till management in a long-term study in southern Spain. Soil Res, 53(2):113-124. https://dx.doi.org/ 10.1071/SR13369

Chatterjee S., Bandyopadhyay K K., Pradhan S., Singh R., Datta S P.,2018. Effects of irrigation, crop residue mulch and nitrogen management in maize (Zea mays, L.) on soil carbon pools in a sandy loam soil of Indo-gangetic plain region. CATENA, 165:207-216. https://doi.org/10.1016/j.catena.2018.02.005

Chaudhary, S., Dheri G S., & Brar B S., 2017. Long-term effects of NPK fertilizers and organic manures on carbon stabilization and management index under rice-wheat cropping system. Soil Till Res, 166, 59-66. https://doi.org/10.1016/j.still.2016.10.005

Chen H X., Hou R X., Gong Y S., Li H W., Fan M S., Kuzyakov Y., 2009. Effects of 11 years of conservation tillage on soil organic matter fractions in wheat monoculture in Loess Plateau of China. Soil Tillage Res, 106(1):85-94. https://doi.org/10.1016/j.still.2009.09.009

Cheng F L., Li X Y., Zhi K K., Zhang Z S., Wang J P., Cao C G., 2012. Short-term effects of conservation management practices on soil labile organic carbon fractions under a rape–rice rotation in central China. Soil Tillage Res,119:31-37. https://doi.org/10.1016/j.still.2011.12.005

Chu P F., Zhang Y L., Yu Z W., Guo Z L., Shi Y., 2016. Winter wheat grain yield, water use, biomass accumulation and remobilisation under tillage in the North China Plain. Field Crops Res, 193:43-53. https://doi.org/10.1016/j.fcr.2016.03.005

De-Cheng L I., Velde B., Feng-Min L I., Zhang G L., Ming-Song Z H A O., Huang L M., 2011. Impact of long-term alfalfa cropping on soil potassium content and clay minerals in a semi-arid loess soil in China. Pedosphere, 21(4), 522-531. https://doi.org/10.1016/S1002-0160(11)60154-9

Ghimire R., Lamichhane S., Acharya B S., Bista P., Sainju U M., 2017. Tillage, crop residue, and nutrient management effects on soil organic carbon in rice-based cropping systems: A review. J Integr Agr, 16(1):1-15. https://doi.org/10.1016/S2095-3119(16)61337-0

Ghosh A., Bhattacharyya R., Meena M C., Dwivedi B S., Singh G., Agnihotri R., Sharma C., 2018. Long-term fertilization effects on soil organic carbon sequestration in an Inceptisol. Soil Tillage R, 177:134-144. https://doi.org/10.1016/j.still.2017.12.006

He L Y., Zhang A F., Wang X D., Li J, Hussain Q., 2019. Effects of different tillage practices on the carbon footprint of wheat and maize production in the Loess Plateau of China. J Clean Prod, 234:297-305. https://doi.org/ 10.1016/j.jclepro.2019.06.161

Hou X Q, Li R, Jia Z K, Han Q F., 2012. Effects of rotational tillage practices on soil structure, organic carbon concentration and crop yields in semi-arid areas of northwest China. Soil Use Manage,aop (aop). https://doi.org/10.1111/j.1475-2743.2012.00429.x

Jharna R S., Bhupinder P., Annette L C, Fang Y Y., 2018. Carbon and nutrient mineralisation dynamics in aggregate-size classes from different tillage systems after input of canola and wheat residues. Soil Biol Biochem, 116:22-38. https://doi.org/10.1016/j.soilbio.2017.09.030

Jiang P K., Xu Q F., Xu Z H., Cao Z H., 2006.Seasonal changes in soil labile organic carbon pools within a Phyllostachys praecox stand under high rate fertilization and winter mulch in subtropical China. For. Ecol. Manag, 236, 30-36. https://doi.org/10.1016/j.foreco.2006.06.010

Johnson M F., Allmaras R R., Reicosky D C., 2006. Estimating Source Carbon from Crop Residues, Roots and Rhizodeposits Using the National Grain-Yield Database. Agronomy Journal, 98(3):622. https://doi.org/10.2134/agronj2005.0179

Kaiser K., Kalbitz K., 2012. Cycling downwards-dissolved organic matter in soils. Soil Biol Biochem, 52(none):29-32. https://doi.org/10.1016/j.soilbio.2012.04.002

Kong A Y Y., Six J., Bryant D C., Denison R F., 2005. The Relationship between Carbon Input, Aggregation, and Soil Organic Carbon Stabilization in Sustainable Cropping Systems. Soil Sci Soc AM J, 69(4):1078. https://doi.org/10.2136/sssaj2004.0215

Kukal S S., Rehana-Rasool., Benbi D K., 2009.Soil organic carbon sequestration in relation to organic and inorganic fertilization in rice–wheat and maize–wheat systems. Soil Tillage Res, 102(1):87-92. https://doi.org/10.1016/j.still.2008.07.017

Leonard L A., Welsh C M., Zeleke T B., 2012. Effect of subsoiling and injection of pelletized organic matter on soil quality and productivity. Canadian Journal of Soil Science, 92(1):269-276. https://doi.org/10.4141/CJSS2011-003

Li J., Wen Y C., Li X H., Li Y T., Yang X D., Lin Z A., Song Z Z., Cooper J M., Zhao B Q., 2018. Soil labile organic carbon fractions and soil organic carbon stocks as affected by long-term organic and mineral fertilization regimes in the North China Plain. Soil Tillage Res, 175:281-290. https://doi.org/10.1016/j.still.2017.08.008

Li S., Li Y B., Li X S., Tian X H., Zhao A Q., Wang S J., Wang S X., Shi J L., 2016. Effect of straw management on carbon sequestration and grain production in a maize -wheat cropping system in Anthrosol of the Guanzhong Plain. Soil Tillage Res, 157:43-51. https://doi.org/10.1016/j.still.2015.11.002

Liang Q., Chen H Q., Gong Y S., Fan M S., Yang H F., Lal R., Kuzyakov Y., 2012. Effects of 15 years of manure and inorganic fertilizers on soil organic carbon fractions in a wheat-maize system in the North China Plain. Nutr Cycl Agroecosyst, 92(1):21-33. https://doi.org/10.1007/s10705-011-9469-6

Lu D., Li C., Sokolwski E., Magen H., Chen X Q., Wang H Y., Zhou J M., 2017. Crop yield and soil available potassium changes as affected by potassium rate in rice–wheat systems. Field Crops Res, 214:38-44. https://doi.org/10.1016/j.fcr.2017.08.025

Lu M., Zhou X H., Luo Y., Yang Y H., Fang C M., Chen J K., Li B., 2011. Minor stimulation of soil carbon storage by nitrogen addition: a meta-analysis. Agr Ecosyst Environ,140:234-244. https://doi.org/10.1016/j.agee.2010.12.010

Luo R Y., Fan J L., Wang W J., Lou J F., Kuzyakov Y., He J S., Chu H Y., Ding W X., 2019. Nitrogen and phosphorus enrichment accelerates soil organic carbon loss in alpine grassland on the Qinghai-Tibetan Plateau. Sci Total Environ, 650:303-312. https://doi.org/10.1016/j.scitotenv.2018.09.038

Maillard É., Mcconkey B G., Luce M S., Angers D A., Fan J L., 2018. Crop rotation, tillage system, and precipitation regime effects on soil carbon stocks over 1 to 30 years in Saskatchewan, Canada. Soil Tillage Res, 177:97-104. https://doi.org/10.1016/j.still.2017.12.001

Manns H R., Berg AA., 2014. Importance of soil organic carbon on surface soil water content variability among agricultural fields. J Hydrol, 516:297-303. https://doi.org/10.1016/j.jhydrol.2013.11.018

Márcio R N., Es H M V., Schindelbeck R., Ristow A J., Ryan M., 2018. No-till and cropping system diversification improve soil health and crop yield. Geoderma, 328:30-43. https://doi.org/10.1016/j.geoderma.2018.04.031

Mazzoncini M., Sapkota TB., Bárberi P., Antichi D., Risaliti R., 2011. Long-term effect of tillage, nitrogen fertilization and cover crops on soil organic carbon and total nitrogen content. Soil Tillage Res. 114, 165-174. https://doi.org/10.1016/j.still.2011.05.001

Nayak A K., Gangwar B., Shukla A K., Mazumdar S P., Kumar A., Raja R., Kumar A., Kumar V., Rai P K., Mohan U., 2012. Long-term effect of different integrated nutrient management on soil organic carbon and its fractions and sustainability of rice–wheat system in Indo Gangetic Plains of India. Field Crops Res, 127(none):129-139. https://doi.org/10.1016/j.fcr.2011.11.011

Nicoloso R S., Rice C W., Amado T J C., Costa C N., Akley E K.,2018. Carbon saturation and translocation in a no-till soil under organic amendments. Agriculture Ecosyst Environ, 264:73-84. https://doi.org/10.1016/j.agee.2018.05.016

Poeplau C., Don A., 2013. Sensitivity of soil carbon stocks and fractions to different land-use changes across Europe. Geoderma, 192(1):189-201. https://doi.org/10.1016/j.geoderma.2012.08.003

Ren X L., Zhang P., Chen X L., Guo J J., Jia Z K., 2016. Effect of different mulches under rainfall concentration system on corn production in the semi-arid areas of the Loess Plateau. Sci Rep. 6, 19019. https://doi.org/10.1038/srep19019

Samuel E., Palmer S M., Chapman P J., 2018. Soil organic carbon stock in grasslands: Effects of inorganic fertilizers, liming and grazing in different climate settings. J Environ Manag, 223:74-84. https://doi.org/10.1016/j.jenvman.2018.06.013

Sauerbeck D R., 2001.CO_2emissions and C sequestration by agriculture–perspectives and limitations. Nutr Cycl Agroecosyst, 60(1-3):253-266. https://doi.org/10.1023/A:1012617516477

Schimel D S., 1995. Terrestrial ecosystems and the carbon cycle.Global Change Biol, 1(1):77-91. https://doi.org/10.1111/j.1365-2486.1995.tb00008.x

Shahid M., Nayak A K., Puree C., Tripathi R., Lal B W., Gautam P., Bhattacharyya P., Mohanty S., Kumar A., Panda B B., Kumar U., Shukla A K.,2017. Carbon and nitrogen fractions and stocks under 41 years of chemical and organic fertilization in a sub-humid tropical rice soil. Soil Tillage Res, 170:136-146. https://doi.org/10.1016/j.still.2017.03.008

Somasundaram J., Reeves S., Wang W J., Heenan M., Dalal R.,2016. Impact of 47- years of No-tillage and stubble retention on soil aggregation and Carbon distribution in a Vertisol. Land Degrad Dev, 5:1589-1602. https://doi.org/ 10.1002/ldr.2689

Srinivasarao C., Deshpande A N., Venkateswarlu B., Lal R., Singh A K., Kundu S., Vittal K P R., Mishra P K., Prasad J V N S., Mandal U K., Sharma K L., 2012. Grain yield and carbon sequestration potential of post monsoon sorghum cultivation in Vertisols in the semi-arid tropics of central India. Geoderma, 175-176(none):0-97. https://doi.org/10.1016/j.geoderma.2012.01.023

Stewart C E., Halvorson A D., Delgado J A., 2017. Long-term N fertilization and conservation tillage practices conserve surface but not profile SOC stocks under semi-arid irrigated corn. Soil Tillage Res, 171:9-18. https://doi.org/10.1016/j.still.2017.04.003

Sun L., Wang S L., Zhang Y J., Li J., Wang X L., Wang R., Lyu W., Chen N N., Wang Q., 2018. Conservation agriculture based on crop rotation and tillage in the semi-arid Loess Plateau, China: Effects on crop yield and soil water use. Agriculture, Ecosyst Environ, 251:67-77. https://doi.org/10.1016/j.agee.2017.09.011

Sun M., Ren A X., Gao Z Q., Wang P R., Mo F., Xue L Z., Lei M M.,2018. Long-term evaluation of tillage methods in fallow season for soil water storage, wheat yield and water use efficiency in semiarid southeast of the Loess Plateau. Field Crops Res, 218:24-32. https://doi.org/10.1016/j.fcr.2017.12.021

Vance F., Brookes P., Jenkinson D.,1987. Microbial biomass measurements in forest soils: the use of the chloroform fumigation–incubation method in strongly acid soils. Soil Biol Biochem,19, 697-702.

https://doi.org/10.1016/0038-0717(87)90051-4

Walkley, A., Black, I. A., 1934. An examination of the degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci, 37(1), 29-38. https://doi.org/10.1097/00010694-193401000-00003

Wang S L., Wang H., Zhang Y H., Wang R., Zhang Y J., Xu Z G., Jia G C., Wang X L., Li J., 2018. The influence of rotational tillage on soil water storage, water use efficiency and maize yield in semi-arid areas under varied rainfall conditions. Agr Water Manag, 203:376-384. https://doi.org/10.1016/j.agwat.2018.03.007

Yang S M., Malhi S S., Song J R., Xiong T C., Yue W Y., Lu L L., Wang G J., Guo T W., 2006. Crop yield, nitrogen uptake and nitrate-nitrogen accumulation in soil as affected by 23 annual applications of fertilizer and manure in the rainfed region of Northwestern China. Nutr Cycl Agroecosyst,76:81-94. https://doi.org/10.1007/s10705-006-9042-x

Yu q., Wang H., Wen P F., Wang S L., LiJ., Wang R., Wang X L. 2020. A suitable rotational conservation tillage system ameliorates soil physical properties and wheat yield: An 11-year in-situ study in a semi-arid agroecosystem. Soil Tillage Res, 199:104600. https://doi.org/10.1016/j.still.2020.104600

Zhao X., Liu S L., Pu C., Zhang X Q., Xue J F., Ren Y X., Zhao X L., Chen F., Lal R., Zhang H L., 2017. Crop yields under no-till farming in China: A meta-analysis. Eur J Agron, 84:67-75. https://doi.org/10.1016/j.eja.2016.11.0

TABLE 1 Content of readily oxidizable C (ROC), dissolved organic C (DOC), microbial biomass C (MBC), and particulate organic C (POC) under different treatments in the different soil layers.

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BF, LF and CF represent balanced fertilization, low fertilization and conventional fertilization, respectively. NS, no-tillage rotated with subsoiling in alternating years; SP, subsoiling rotated with ploughing in alternating years; PN, ploughing rotated with no-tillage in alternating years; PP, ploughing applied every year. Different lowercase letters in the same columns stand for statistical difference (at 5% level) among different treatments. ns, not significant.

TABLE 2 SOC lability (L), SOC lability index (LI), C pool index (CPI) and C pool management index (CMI) under different treatments.

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