Increasing soil organic carbon pools and wheat yields by optimising tillage and fertilisation on the Loess Plateau in China

Xia Zhang | Minge Wang | Dandan Zhang | Yulin Zhang | Xudong Wang

1College of Natural Resources and Environment, Northwest A&F University, Yangling, China
2Key Laboratory of Plant Nutrition and Agri-environment in Northwest China, Ministry of Agriculture, Yangling, China

Correspondence
Xudong Wang and Yulin Zhang, College of Natural Resources and Environment, Northwest A&F University, Yangling 712100, Shaanxi, China. Email: wangxudong01@126.com (X. W.); yulinzhangbest@126.com (Y. Z.)

Funding information
Special Fund for Agro-scientific Research in the Public Interest of the Ministry of Agriculture, China, Grant/Award Number: 201503116

Abstract
The effect of conservation tillage on soil organic carbon (SOC) sequestration and crop production is controversial in semi-arid areas. In addition, fertilisation is another essential factor affecting soil carbon pool and crop yields. We sought to explore the changes of SOC pool and crop productivity after optimising fertilisation and tillage. An 11-year field experiment on the Loess Plateau in China was conducted to evaluate the effects of (i) fertilisation (balanced fertilisation, low fertilisation, conventional fertilisation) and (ii) tillage (no-tillage, subsoiling, ploughing) on input-C, SOC stocks, labile C fractions, C pool management index (CMI) and wheat yield. SOC stock accumulation at 0–35 cm depth under balanced fertilisation increased by 59% compared to conventional fertilisation due to the larger amount and stabilisation efficiency of input-C. Simultaneously, balanced fertilisation increased labile C contents and CMI at 0–10 cm depth. For tillage, no-tillage and subsoiling improved input-C and its stabilisation efficiency, and increased SOC stocks compared to ploughing. Balanced fertilisation combined with no-tillage or subsoiling produced greater SOC stocks at 0–35 cm depth compared to other treatments. No-tillage increased labile C contents and CMI at 0–10 cm depth, while subsoiling increased labile C contents and CMI at 0–10 and 35–50 cm depths. Wheat yield and sustainable yield index (SYI) were positively correlated with SOC, and the effect of SOC contributed to SYI largely through indirect effects of dissolved organic C and particulate organic C. Wheat yield and SYI were increased by optimising fertilisation and tillage, and the greatest yield was under balanced fertilisation combined with the subsoiling treatment. Our findings suggested that balanced fertilisation combined with subsoiling was an effective practice for increasing SOC sequestration, soil quality, wheat yields and had great potential application on the Loess Plateau in China.

Highlights
• C sequestration under conservation tillage and fertilisation are controversial in semi-arid areas.
Balanced fertilisation promoted SOC sequestration in no-tillage and subsoiling treatments. 
Subsoiling improved soil quality at 0–10 and 35–50 cm depths due to the greater SOC and labile C. 
Subsoiling was superior to no-tillage and ploughing in maintaining crop productivity.

**KEYWORDS**
C pool management index, fertilisation, no-tillage, organic carbon fractions, soil organic carbon sequestration, subsoiling, yield stability

### 1 | INTRODUCTION

Soil is the largest reservoir of terrestrial organic carbon (~1580 Gt C), and it is reported that approximately 20% of global CO₂ emissions originate from soils (Rastogi et al., 2002; Schimel, 1995). Furthermore, soil organic carbon (SOC) is a key indicator of soil fertility and health, which affects food production (Lal, 2004). Sequestering SOC is a win–win strategy of reducing CO₂ emissions and securing food production. In general, SOC sequestration can be enhanced by reducing the mineralisation rate of SOC and increasing C input (Li, Wen, et al., 2018; Xie et al., 2017). Conservation tillage (i.e. no tillage, subsoiling and minimum tillage) decreased the rate of SOC mineralisation due to reduced soil disturbance, which in turn increased SOC content (Jat et al., 2019; Rahmati et al., 2020). However, the lack of soil mixing during long-term no-tillage would lead to SOC accumulating in surface soil, and may not ensure an increase of SOC stock in the whole soil profile (Niu et al., 2019; Stewart et al., 2017). Meanwhile, the effect of fertilisation on SOC sequestration is also controversial. Many studies have shown that inorganic fertiliser application is effective in increasing SOC storage (He et al., 2018; Xie et al., 2018), while some studies have reported that chemical fertilisation weakens SOC physical protection and accelerates the decomposition of SOC (Ghosh et al., 2018; Liu & Zhou, 2017). In addition, some studies suggested that the increase in the amount of crop residues returned to the field under conservation tillage or fertilisation is another reason for the increase of SOC sequestration (Nash et al., 2018; Stewart et al., 2018). Wang et al. (2018a) reported that due to the greater crop residues inputs, SOC content under no-tillage and subsoiling management is 12.5% and 11.6% greater, respectively, than that under conventional tillage. Lou et al. (2011) found that the effect of C-sequestration under chemical fertilisation with straw returning was significant compared to that without straw returning. Therefore, quantifying the amounts and stabilisation rate of crop residues under different tillage and fertilisations is essential for studying the change of SOC.

Soil labile organic C fractions [i.e. readily oxidisable C (ROC), dissolved organic C (DOC), microbial biomass C (MBC) and particulate organic C (POC)] are early and sensitive indicators of SOC change, and can promote microbial activity and nutrient cycling (Duval et al., 2018). Tillage and fertilisation are important factors affecting the changes in SOC labile pool. Many studies found that conservation tillage showed promising trends to increase soil labile organic C fractions (Bongiorno et al., 2018; Prasad et al., 2016). Furthermore, the positive effects of fertilisation on soil labile C pools have also been reported (Benbi et al., 2015; Tang et al., 2018). Chaudhary et al. (2017) found that soils fertilised over the long term contained greater levels of ROC, DOC and POC than unfertilised soils. On the contrary, some studies have questioned whether conservation tillage or inorganic fertiliser application actually increase soil labile C fractions (Li et al., 2012; Li, Wu, et al., 2018). Carbonell-Bojollo et al. (2015) and Huang et al. (2015) have reported that no-tillage has no significant positive effect on the soil labile C pool due to the reduction of labile C content in subsoil layer. Liu et al. (2018) observed that long-term inorganic fertilisation caused the decomposition of the labile C fractions, and increased the loss of the labile C fractions. These inconsistent results may be related to climate, soil type, crop system, experimental duration and other factors (Samuel et al., 2018; Tondello, 2007). Therefore, studies of the effects of tillage or fertilisation on SOC labile pool should be adapted to local conditions.

The Loess Plateau, which has a land area of $6.2 \times 10^5$ km² located in the northwest of China. Winter wheat (*Triticum aestivum* L.) is one of the major grain crops in this region (Ren et al., 2016). However, soil productivity is poor because of low SOC, severe water stress, erratic weather condition and severe environmental degradation.
in this area (Wang et al., 2018b). Conservation tillage has played a positive role in improving soil conditions and increasing crop yields (Gollany and Polumsky, 2018; Peng et al., 2020), and has been widely used in recent years. Nevertheless, Sun et al. (2018) and Wang et al. (2018b) observed that no-tillage led to crop yield reduction compared to conventional tillage on the Loess Plateau in China. In addition, in order to pursue short-term large crop yields, farmers have always adopted a fertilising mode of high nitrogen and phosphorus application in this region, which is not conducive to sustainable soil production. Therefore, it is essential to optimise tillage and fertilisation to increase SOC sequestration while improving crop yields and enhancing agricultural sustainability on the Loess Plateau in China.

We hypothesised that optimising tillage and fertilisation can improve soil quality and productivity, and increase SOC and soil labile C pools by increasing the amount of crop residues returned to the field. In this study, a 11-year (2007–2017) long-term field experiment with different tillage and fertilisation modes in the Loess Plateau was established to achieve the following objectives: (1) to study the change of SOC accumulation, soil labile organic C fractions content, C pool management index (CMI) and wheat yield in long-term tillage and fertilisation experiment; and (2) to find the optimal mode of tillage and fertilisation to increase SOC sequestration, improve soil quality and increase wheat yield for the regions with similar climate and soil conditions in arid and semiarid areas.

2 | MATERIALS AND METHODS

2.1 | Site description

The field experiment was conducted from September 2007 to June 2017 at the Dryland Agricultural Research Station of Northwest A&F University, which was located in Heyang County, Shaanxi Province, China (104°04′E, 35°19′N; altitude 877 m). The research station was located in the Loess Plateau, which is characterised by a temperate semi-arid continental monsoon climate. Over the last 30 years, the annual mean temperature was 11.5°C and the annual frost-free period was 210 days. The mean annual precipitation and evaporation were 536.6 and 1833 mm, respectively. The soil was classified as Chromic Cambisol according to the FAO/UNESCO Soil Classification (1993), which consists of 271 g kg⁻¹ clay, 390 g kg⁻¹ silt and 339 g kg⁻¹ sand. The main soil characteristics in 0–50 cm before the experiment are represented in Table 1.

2.2 | Experimental design and treatments

This experiment was carried out from September 2007 to June 2017 in a winter wheat continuous cropping system. A split plot design was adopted. The main plot treatment was fertilisation treatment, including three types: balanced fertilisation (150 N kg ha⁻¹, 120 P₂O₅ kg ha⁻¹ and 90 K₂O kg ha⁻¹), low fertilisation (75 N kg ha⁻¹, 60 P₂O₅ kg ha⁻¹ and 45 K₂O kg ha⁻¹) and conventional fertilisation (225 N kg ha⁻¹, 180 P₂O₅ kg ha⁻¹ and no potassium fertiliser). The fertiliser types for N, P₂O₅ and K₂O were urea, ammonium phosphate and potassium sulphate, respectively. The full rates of nitrogen (N), phosphorus (P) and potassium (K) were applied as basal fertiliser on the sowing date for wheat. The subplot treatment was tillage systems, which also included three types: no-tillage (the crop residue was chopped and covered on the soil surface following the harvest of the previous crop, soil disturbance was avoided until sowing), subsoiling (the crop residue was chopped and covered on the soil surface following the harvest of the previous crop, and the soil was subsoiled to a depth of 30–35 cm using a subsoiler with intervals of 60 cm), ploughing (the crop residue was chopped, the soil was tilled to 20–25 cm depth using a tractor-mounted mouldboard plough and the crop residue were buried into the 20–25 cm layer). The two factors (fertilisation and tillage) are combined into nine treatments with three replications. The size of the individual plot was 22.5 m × 5 m. The crop planting pattern was one season per year. Winter wheat (Jinmai 47) was sowed at the end of September and harvested at the early of June next year. The row spacing of winter wheat was 20 cm, and the seeding rate of winter wheat was 150 kg ha⁻¹. Other farming practices were similar to the local practices in this experiment.

2.3 | Soil sampling and processing

All soil samples (0–10, 10–20, 20–35 and 35–50 cm) were collected from three randomly selected positions using a soil auger under different treatments in June 2017 after winter wheat harvest. Then the soil samples were mixed thoroughly to divide them into two subsamples. One part was stored at 4°C for the determination of MBC and SOC. The other part was air-dried and passed through a 0.25-mm sieve for analysing the SOC, ROC and POC. The SOC content was determined using the K₂CrO₇-H₂SO₄ digestion method (Walkley & Black, 1934). ROC was measured using the 333 mmol L⁻¹ KMnO₄ oxidation method (Blair et al., 1995). DOC was extracted from 10 g of moist soil with a 1:5 ratio of soil to water at 25.8°C
MBC was determined using the CHCl₃ fumigation-extraction method (Vance et al., 1987). POC was determined using modifications of the method described by Cambardella and Elliott (1992). The soil bulk density was measured using metal rings (volume 100 cm³) method (Doran & Jones, 1996).

SOC stock was calculated based on the equivalent soil mass method (Ellert & Bettany, 1995):

\[
M_{\text{soil},i} = \rho_i \times T_i \times 10,000, \tag{1}
\]

\[
M_{\text{stock}} = \sum_{i=1}^{n} [M_{\text{soil},i} \times \text{conc}_i + (M_{m,i} - M_{\text{soil},i}) \times \text{conc}_{i+1}] \times 0.001, \tag{2}
\]

where \( M_{\text{soil},i} \) (Mg ha⁻¹) is the soil mass of layer \( i \), \( \rho_i \) (g cm⁻³) is soil bulk density of layer \( i \), \( T_i \) (m) is the soil layer thickness of layer \( i \). \( M_{m,i} \) (Mg ha⁻¹) is the maximum soil mass of layer \( i \). \( \text{conc}_i \) and \( \text{conc}_{i+1} \) (g kg⁻¹) are the SOC content of layer \( i \) and \( i+1 \), respectively. Only the SOC stock in the 0–35 cm layer can be calculated by the equivalent soil mass method.

Carbon management index (CMI) was calculated using the following equations (Blair et al., 1995) with CF + PT treatment as the reference soil sample.

\[
L = \frac{\text{ROC}_c}{\text{SOC}_c}, \tag{3}
\]

\[
\text{CPI} = \frac{\text{SOC}_s}{\text{SOC}_r}, \tag{4}
\]

\[
\text{LI} = \frac{L_c}{L_R}, \tag{5}
\]

\[
\text{CMI} = \frac{\text{CPI} \times \text{LI} \times 100.} \tag{6}
\]

### 2.4 | Estimation of plant biomass carbon inputs

The yield and straw of crop were determined by manual harvesting, threshing and air-drying from three 3-m² areas taken at random in each plot for winter wheat.

\[
\text{Total C input} = C_{\text{straw}} + C_{\text{root}} + C_{\text{rhizodep}}. \tag{7}
\]

The C input from straw, \( C_{\text{straw}} \), was estimated as:

\[
C_{\text{straw}} = B_{\text{straw}} \times 0.45, \tag{8}
\]

where \( B_{\text{straw}} \) (Mg ha⁻¹) is crop straw biomass. The plant biomass C input was evaluated by considering a C content of 45% in the plant tissues by Johnson et al. (2006).

The C input from roots, \( C_{\text{root}} \), was calculated as:

\[
C_{\text{root}} = B_{\text{straw}} \times r \times 0.45, \tag{9}
\]

where \( r \) is the root to straw ratio. Wheat root represented 22% of straw biomass (Kong et al., 2005).

The C input from rhizodeposition (\( C_{\text{rhizodep}} \)) was calculated according to the formula (Maillard et al., 2018):

\[
C_{\text{rhizodep}} = C_{\text{root}} \times 0.65. \tag{10}
\]

The stabilisation efficiency (\( S_e, \% \)) of plant biomass carbon into SOC in the 0–35 cm soil layer was calculated according to the equation (Srinivasarao et al., 2012):

\[
S_e = \frac{\Delta \text{SOC}_{\text{stock}}}{C_{\text{input}}}, \tag{11}
\]

where \( \Delta \text{SOC}_{\text{stock}} \) (Mg ha⁻¹) is the SOC stock accumulation during the 11-year experiment, \( C_{\text{input}} \) (Mg ha⁻¹) is total plant biomass C input.

The sustainable yield index (SYI) of wheat was calculated for the treatments taking into consideration the

### Table 1  Physical and chemical properties of tested soil before beginning of experiment in 2007

| Soil depth (cm) | Soil organic carbon (g kg⁻¹) | Total nitrogen, N (g kg⁻¹) | Total phosphorus, P (g kg⁻¹) | Total K (g kg⁻¹) | Soil bulk density (g cm⁻³) |
|----------------|-----------------------------|---------------------------|-----------------------------|-----------------|---------------------------|
| 0–10           | 7.44                        | 0.72                      | 0.62                        | 5.95            | 1.38                      |
| 10–20          | 7.35                        | 0.64                      | 0.57                        | 5.88            | 1.48                      |
| 20–35          | 5.85                        | 0.55                      | 0.21                        | 5.56            | 1.58                      |
| 35–50          | 4.34                        | 0.48                      | 0.09                        | 5.62            | 1.57                      |
yield data of the 11 years using the following formula (Ghosh et al., 2012):

\[
SYI = \frac{Y - \sigma}{Y_{\text{max}}},
\]

where \(Y\) (kg ha\(^{-1}\)) represents the mean yield over the years, \(\sigma\) is the standard deviation and \(Y_{\text{max}}\) (kg ha\(^{-1}\)) is the maximum yield of the area.

2.5 Statistical analysis

SAS (SAS Systems, Cary, NC, USA) and Microsoft excel 2007 (Microsoft Corporation, USA) was used to carry out data processing and statistical analysis. The effects of the different treatments on C input, SOC, soil labile organic C fractions (ROC, DOC, MBC and POC), CMI, wheat yield and SYI were analysed using ANOVA with the Duncan multiple range test. Path coefficient analysis was made on the basis of correlation coefficients taking SYI as effect and the SOC and soil labile organic C fractions as cause. Direct and indirect effects of SOC and soil labile organic C fractions on SYI were worked out using path coefficient analysis. Experimental means were compared at the 95% probability level and the correlations between indexes were analysed using SAS.

3 RESULTS

3.1 Total C input from crop residue

The C input from crop residue (including straw, roots and rhizodeposition) during 11-year after the implementation of each treatment is shown in Figure 1. Overall, the fertilisation and tillage systems significantly affected C input. The total C input increased by 13% in balanced fertilisation and 8% in conventional fertilisation compared to low fertilisation. Compared to ploughing, the total C input significantly increased by 5% and 7% in no-tillage and subsoiling, respectively (\(p < 0.05\)).

3.2 Soil organic carbon

The SOC stocks at 0–35 cm depth in all treatments increased after the 11-year experiment. The maximum increment (7.8 Mg ha\(^{-1}\)) was found in the treatment of BF + NT, while the minimum increment (3.4 Mg ha\(^{-1}\)) was found in the treatment of CF + PT (Figure 3). Overall, the effect of fertilisation on SOC content and SOC stocks was significant (\(p < 0.05\), Figures 2 and 3). Compared to conventional fertilisation, balanced fertilisation markedly increased the SOC content at all soil depths (0–50 cm). At 0–35 cm depth, the SOC stock was 6% and 7% greater in balanced fertilisation than that in conventional fertilisation and low fertilisation, respectively (\(p < 0.05\)).

3.3 Stabilisation efficiency of crop residue C

The proportion of SOC stock accumulation to total C input is the stabilisation efficiency of crop residue C (Figure 4, \(p < 0.05\)). After the 11-year experiment, the difference of stabilisation efficiency among all treatments was statistically significant. The greatest stabilisation efficiency was observed in the BF + NT treatment, which was 2.1 times greater than CF + PT treatment.
Fertilisation and tillage had significant effects on stabilisation efficiency, but the interaction between them was slight. For fertilisation, the stabilisation efficiency was markedly greater in balanced fertilisation than that in low fertilisation and conventional fertilisation \((p < 0.05)\). For tillage, the stabilisation efficiency increased by 28% and 11% in no-tillage and subsoiling compared to ploughing, respectively \((p < 0.05)\).

Regression analysis showed a significantly positive correlation between SOC stock accumulation and total C input, and the stabilisation efficiency of crop residue C (Figure 5, \(p < 0.05\)).

### 3.4 Soil labile organic C fractions

Significant effects on ROC content due to fertiliser systems were detected at the 0–10, 10–20, 20–35 and 35–50 cm soil depths, ROC content was the greatest in balanced fertilisation, followed by conventional fertilisation and low fertilisation (Table 2). Tillage had significant effect on ROC at all soil depths (0–50 cm). The ROC content in no-tillage and subsoiling was significantly greater than that in ploughing at the 0–10 cm depth, and the subsoiling also significantly increased ROC content at 35–50 cm depth, while the ROC content in no-tillage and
subsoiling was significantly lesser than that in ploughing at 10–20 cm depth \((p < 0.05)\).

The effects of the fertilisation systems and tillage measures on DOC content were significant (Table 2). Compared to conventional fertilisation, balanced fertilisation increased DOC content in each layer of 0–50 cm, while low fertilisation significantly decreased DOC content at 35–50 depth \((p < 0.05)\). For tillage, no-tillage and subsoiling significantly increased DOC content compared to ploughing at 0–10 and 10–20 cm depths \((p < 0.05)\). At 20–35 cm depth, the DOC content in ploughing was significantly greater than that in no-tillage and subsoiling \((p < 0.05)\). Simultaneously, DOC content in subsoiling was 42% and 22% greater than that in no-tillage and ploughing at 35–50 cm depth, respectively \((p < 0.05)\).

In Table 2, MBC content was significantly greater in balanced fertilisation and conventional fertilisation than that in low fertilisation at all soil depths in 0–50 cm \((p < 0.05)\). Compared to conventional fertilisation, balanced fertilisation markedly increased MBC content by 6% at 0–10 cm depth \((p < 0.05)\). For tillage, no-tillage and subsoiling significantly increased MBC content compared to ploughing at 0–10 cm and 10–20 cm depths \((p < 0.05)\). At 20–35 cm depth, MBC content was the greatest in ploughing, followed by subsoiling and no-tillage, and there were statistical differences among three tillage treatments \((p < 0.05)\). At 35–50 cm depth, MBC content in subsoiling was significantly greater than that in ploughing and no-tillage \((p < 0.05)\).

Fertilisation significantly affected POC content (Table 2). POC content was the greatest in the balanced fertilisation, followed by conventional fertilisation and low fertilisation at all soil depths in 0–50 cm, and there were statistical differences among three fertilisation treatments at 0–10, 10–20 and 20–35 cm depths \((p < 0.05)\). For tillage, POC content markedly increased by 55% and 32% in no-tillage and subsoiling compared to ploughing at 0–10 cm depth, respectively \((p < 0.05)\). At the 10–20 cm depth, POC content in ploughing was significantly greater than that in subsoiling and no-tillage \((p < 0.05)\). At 20–35 cm and 35–50 cm depths, POC content was the greatest in subsoiling, followed by ploughing and no-tillage, and there were statistical differences among three tillage treatments \((p < 0.05)\).

### 3.5 Carbon pool management index

After 11 years, the SOC lability \((L)\) and SOC lability index \((LI)\) at all soil depths in 0–50 cm were larger in balanced fertilisation and conventional fertilisation than those in
### Table 2

Content of readily oxidisable C (ROC), dissolved organic C (DOC), microbial biomass C (MBC) and particulate organic C (POC) under different treatments in the 0–10, 10–20, 20–35 and 35–50 cm soil layers

| Soil management | ROC (g kg\(^{-1}\)) | DOC (mg kg\(^{-1}\)) | MBC (mg kg\(^{-1}\)) | POC (g kg\(^{-1}\)) |
|-----------------|----------------------|----------------------|----------------------|----------------------|
|                 | 0–10 cm | 10–20 cm | 20–35 cm | 35–50 cm | 0–10 cm | 10–20 cm | 20–35 cm | 35–50 cm | 0–10 cm | 10–20 cm | 20–35 cm | 35–50 cm | 0–10 cm | 10–20 cm | 20–35 cm | 35–50 cm |
| **Fertilisation (F)** | | | | | | | | | | | | | | | | | |
| BF              | 2.78\(^b\) | 1.83\(^b\) | 1.25\(^a\) | 0.91\(^a\) | 58.6\(^a\) | 42.0\(^a\) | 30.3\(^a\) | 21.7\(^a\) | 290.4\(^a\) | 174.6\(^a\) | 119.8\(^b\) | 50.5\(^b\) | 2.38\(^a\) | 1.71\(^a\) | 1.19\(^a\) | 0.70\(^a\) |
| LF              | 2.50\(^b\) | 1.66\(^b\) | 1.06\(^c\) | 0.80\(^a\) | 48.6\(^b\) | 36.5\(^b\) | 25.7\(^b\) | 18.1\(^c\) | 249.1\(^c\) | 154.8\(^b\) | 109.3\(^b\) | 44.3\(^c\) | 2.10\(^c\) | 142\(^c\) | 0.94\(^c\) | 0.56\(^b\) |
| CF              | 2.58\(^b\) | 1.73\(^ab\) | 1.18\(^b\) | 0.84\(^a\) | 51.2\(^b\) | 37.5\(^b\) | 28.7\(^b\) | 19.7\(^b\) | 273.1\(^b\) | 183.0\(^a\) | 132.2\(^a\) | 55.6\(^b\) | 2.22\(^b\) | 1.52\(^b\) | 1.03\(^b\) | 0.61\(^b\) |
| **Tillage (T)** | | | | | | | | | | | | | | | | | |
| NT              | 3.24\(^a\) | 1.58\(^c\) | 1.04\(^b\) | 0.75\(^c\) | 62.1\(^a\) | 39.4\(^a\) | 22.7\(^c\) | 16.6\(^c\) | 335.6\(^a\) | 180.5\(^a\) | 99.7\(^c\) | 44.8\(^c\) | 2.68\(^a\) | 1.41\(^c\) | 0.91\(^c\) | 0.51\(^c\) |
| ST              | 2.58\(^b\) | 1.75\(^b\) | 1.23\(^a\) | 0.97\(^a\) | 54.3\(^b\) | 40.9\(^a\) | 29.5\(^b\) | 23.6\(^a\) | 278.4\(^b\) | 176.7\(^b\) | 123.2\(^b\) | 55.9\(^a\) | 2.28\(^b\) | 1.59\(^b\) | 1.20\(^a\) | 0.73\(^a\) |
| PT              | 2.03\(^c\) | 1.88\(^a\) | 1.21\(^a\) | 0.84\(^b\) | 42.0\(^b\) | 35.7\(^b\) | 32.5\(^a\) | 19.3\(^b\) | 198.6\(^c\) | 155.3\(^b\) | 138.3\(^a\) | 49.7\(^b\) | 1.73\(^c\) | 1.66\(^a\) | 1.04\(^b\) | 0.63\(^b\) |

**ANOVA**

| F   | 0.002 | 0.027 | <0.001 | 0.162 | 0.004 | 0.003 | 0.037 | 0.003 | <0.001 | 0.002 | 0.013 | 0.002 | 0.002 | <0.001 | 0.001 | 0.001 | 0.005 |
| T   | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | 0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 |
| P*T | ns    | ns    | ns    | ns    | ns    | ns    | ns    | ns    | ns    | ns    | ns    | ns    | ns    | 0.009 | 0.043 | ns    |

*Note:* Letters indicate statistical difference among different treatments (p < 0.05).

*Abbreviations:* BF, balanced fertilisation; CF, conventional fertilisation; LF, low fertilisation; ns, not significant; NT, no tillage; PT, ploughing; ST, subsoiling.
| Treatment | CPI 0-10 cm | CPI 10-20 cm | CPI 20-35 cm | CPI 35-50 cm | L 0-10 cm | L 10-20 cm | L 20-35 cm | L 35-50 cm | LI 0-10 cm | LI 10-20 cm | LI 20-35 cm | LI 35-50 cm | CMI 0-10 cm | CMI 10-20 cm | CMI 20-35 cm | CMI 35-50 cm |
|-----------|-------------|-------------|-------------|-------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| **Fertilisation (F)** | | | | | | | | | | | | | | | | |
| BF        | 1.28<sup>a</sup> | 1.03<sup>a</sup> | 1.06<sup>a</sup> | 1.13<sup>a</sup> | 0.330<sup>a</sup> | 0.271<sup>a</sup> | 0.238<sup>a</sup> | 0.222<sup>a</sup> | 1.08<sup>a</sup> | 0.94<sup>ab</sup> | 1.00<sup>a</sup> | 0.97<sup>a</sup> | 139.0<sup>a</sup> | 96.6<sup>a</sup> | 105.1<sup>a</sup> | 109.1<sup>a</sup> |
| LF        | 1.20<sup>b</sup> | 0.96<sup>b</sup> | 0.98<sup>b</sup> | 1.05<sup>b</sup> | 0.314<sup>b</sup> | 0.259<sup>a</sup> | 0.215<sup>b</sup> | 0.209<sup>a</sup> | 1.02<sup>b</sup> | 0.90<sup>b</sup> | 0.90<sup>b</sup> | 0.91<sup>a</sup> | 123.8<sup>b</sup> | 85.5<sup>b</sup> | 88.0<sup>c</sup> | 95.5<sup>b</sup> |
| CF        | 1.17<sup>b</sup> | 0.95<sup>b</sup> | 0.98<sup>b</sup> | 1.03<sup>b</sup> | 0.338<sup>a</sup> | 0.276<sup>a</sup> | 0.242<sup>a</sup> | 0.225<sup>a</sup> | 1.10<sup>a</sup> | 0.95<sup>a</sup> | 1.02<sup>a</sup> | 0.98<sup>a</sup> | 129.9<sup>b</sup> | 91.6<sup>ab</sup> | 100.0<sup>b</sup> | 101.3<sup>ab</sup> |
| **Tillage (T)** | | | | | | | | | | | | | | | | |
| NT        | 1.41<sup>a</sup> | 0.94<sup>c</sup> | 0.95<sup>c</sup> | 1.00<sup>c</sup> | 0.359<sup>b</sup> | 0.256<sup>b</sup> | 0.217<sup>b</sup> | 0.202<sup>b</sup> | 1.17<sup>a</sup> | 0.89<sup>b</sup> | 0.91<sup>b</sup> | 0.88<sup>b</sup> | 165.3<sup>a</sup> | 82.7<sup>c</sup> | 86.5<sup>b</sup> | 88.6<sup>c</sup> |
| ST        | 1.21<sup>b</sup> | 0.98<sup>b</sup> | 1.00<sup>b</sup> | 1.15<sup>a</sup> | 0.324<sup>b</sup> | 0.268<sup>ab</sup> | 0.249<sup>a</sup> | 0.234<sup>a</sup> | 1.06<sup>b</sup> | 0.93<sup>ab</sup> | 1.05<sup>a</sup> | 1.02<sup>a</sup> | 128.3<sup>b</sup> | 90.8<sup>b</sup> | 104.7<sup>a</sup> | 117.0<sup>a</sup> |
| PT        | 1.02<sup>c</sup> | 1.03<sup>a</sup> | 1.06<sup>a</sup> | 1.06<sup>b</sup> | 0.299<sup>c</sup> | 0.282<sup>a</sup> | 0.229<sup>b</sup> | 0.219<sup>ab</sup> | 0.97<sup>c</sup> | 0.98<sup>a</sup> | 0.96<sup>b</sup> | 0.95<sup>ab</sup> | 99.1<sup>c</sup> | 100.3<sup>a</sup> | 101.8<sup>a</sup> | 100.3<sup>b</sup> |
| **ANOVA** | | | | | | | | | | | | | | | | |
| F         | 0.009 | 0.011 | <0.001 | <0.001 | 0.018 | ns | 0.002 | ns | 0.019 | ns | 0.004 | ns | 0.008 | 0.039 | <0.001 | ns |
| T         | <0.001 | <0.001 | <0.001 | <0.001 | <0.001 | 0.034 | 0.005 | 0.009 | <0.001 | 0.046 | 0.003 | 0.007 | <0.001 | <0.001 | <0.001 | <0.001 |
| F*T       | <0.001 | <0.001 | <0.001 | <0.001 | ns | ns | ns | ns | ns | ns | ns | ns | 0.032 | ns | 0.049 | ns |

**Note:** Letters indicate statistical difference among different treatments (p < 0.05).

**Abbreviations:** BF, balanced fertilisation; CF, conventional fertilisation; CMI, C pool management index; CPI, C pool index; L, SOC lability; LF, low fertilisation; LI, SOC lability index; ns: not significant; NT, no tillage; PT, ploughing; ST, subsoiling.
low fertilisation, whereas the C pool index (CPI) and carbon pool management index (CMI) was smaller in conventional fertilisation and low fertilisation than those in balanced fertilisation (Table 3). For tillage effect, the L, LI, CPI and CMI were the largest in no-tillage, followed by subsoiling and ploughing, and there were statistical differences among three tillage treatments \((p < 0.05)\). Meanwhile, at 10–20 and 20–35 cm depths, The L, LI, CPI and CMI were the largest in no-tillage, followed by subsoiling and ploughing, and there were statistical differences among three tillage treatments \((p < 0.05)\). At 35–50 cm depth, subsoiling had larger L, LI, CPI and CMI than ploughing and no-tillage \((p < 0.05)\).

### 3.6 | Yield and SYI

Table 4 showed the effects of fertilisation and tillage on wheat yield from 2008 to 2017. For fertilisation effect, balanced fertilisation had the greater wheat yield, with an average increase of 9\% in 2008–2017 compared to conventional fertilisation (Figure 6). Simultaneously, the wheat yield in no-tillage and subsoiling was markedly greater than that in ploughing. Specifically, wheat yield on average increased by 6\% and 9\% in no-tillage and subsoiling compared to ploughing, respectively. On the whole, the minimum average yield of wheat \((4231 \text{ kg ha}^{-1})\) was found in the treatment of LF + PT, while the maximum average yield of wheat \((5260 \text{ kg ha}^{-1})\) was found in the treatment of BF + ST.

The SYI was strongly affected by fertilisation treatments and tillage systems (Figure 6). The value of SYI ranged from 0.544 (LF + PT treatment) to 0.724 (BF + ST treatment). SYI was 10\% and 18\% greater in balanced fertilisation than that in conventional fertilisation and low fertilisation, respectively. Meanwhile, SYI significantly increased by 5\% and 12\% in no-tillage and subsoiling compared to ploughing, respectively \((p < 0.05)\).

### 3.7 | Correlations between wheat yield, SYI and input C, SOC, soil labile organic C fractions and CMI

Significantly positive correlations were found between wheat yield and SOC, ROC, DOC, MBC, POC, CMI and input C (Table 5). In addition, the SYI was also significantly correlated with SOC, ROC, DOC, MBC, POC, CMI and input C. Specifically, the correlation coefficients were partitioned into direct and indirect effects (Table 6). Results of path analysis showed that DOC and POC had strong positive direct effects (0.47 and 0.26) on SYI. The effect of SOC was significantly positive and contributed to wheat yield largely through indirect effects of DOC and POC.

### 4 | DISCUSSION

#### 4.1 | Long-term tillage and fertilisation impact on SOC contents and stocks

After the 11-year experiment, balanced fertilisation combined with conservation tillage (BF + NT and BF + ST treatments) produced greater SOC stocks at 0–35 cm depth than other treatments, indicating that balanced...
Fertilisation promoted SOC sequestration under no-tillage and subsoiling treatments. Previous studies showed that the effect of fertilisation on SOC sequestration depended on the net effect between the increase of soil C inputs by crop residues and the stimulation of SOC decomposition (Maillard et al., 2018; Stewart et al., 2017). In this study, balanced fertilisation produced greater amounts of crop residue C than conventional fertilisation and low fertilisation. The reason for this difference is that compared to only N and P fertiliser, the balanced application of N, P and K fertilisers could provide comprehensive nutrients for crops, was conducive to crop growth and increased the amount of crop residues returned into the field (Yan et al., 2013). Under low fertilisation, the fertiliser application rate was half of that in balanced fertilisation, which was too low to meet the growth needs.
of crops. The greater crop residue C under balanced fertilisation resulted in the increase of SOC sequestration. Using regression analysis, it was observed that the linear correlation coefficient between SOC stock accumulation and input C \( R^2 = 0.399 \) was smaller than that between SOC stock accumulation and the stabilisation efficiency of input C \( R^2 = 0.962 \), indicating that the increase of SOC is more likely related to the stabilisation efficiency of input C. Our study showed that balanced fertilisation and low fertilisation produced greater stabilisation efficiency of input C than conventional fertilisation, leading to greater level of SOC. The reason for this phenomenon is that excessive application of N fertiliser under conventional fertilisation reduced the ratio of C:N in soil (Liu et al., 2020), which accelerates the decomposition of crop residue by soil microorganisms, resulting in a lesser carbon sequestration (Hamer et al., 2009; Lu et al., 2011). In addition, appropriate application of chemical fertiliser increases SOC content, whereas long-term high rates of fertiliser destroys soil aggregates, weakens the physical protection of SOC and decreases SOC stability, thus increasing SOC decomposition (Li, Hou, et al., 2018; Luo et al., 2019; Sithole et al., 2019). This explains our result that a greater SOC content was recorded under balanced fertilisation.

Our results showed that no-tillage and subsoiling markedly increased the SOC stock at 0–35 cm depth compared to ploughing. That is mainly related to the less soil disturbance. Jat et al. (2019) and Xu et al. (2019) reported that due to the reduction of soil disturbance, no-tillage and subsoiling improved soil structure and reduced the accessibility of SOC to microorganisms, leading to the decrease of SOC mineralisation. Furthermore, crop residues are the carbon source of the soil, and no-tillage and subsoiling improved soil properties and enhanced soil fertility, which supported the production of more crop residues (He et al., 2019). Meanwhile, returned crop residues cover the soil surface, and could decrease soil erosion and water evaporation, and maintain soil temperature, thus promoting the humification of crop residues returned to the soil (Ding et al., 2006). Our results showed that compared to ploughing, no-tillage and subsoiling produced greater SOC sequestration by increasing the amount and stabilisation efficiency of crop residue C. In particular, no-tillage with less crop residue input had greater stabilisation efficiency of crop residue C than that in subsoiling, and consequently, no-tillage was superior to subsoiling in increasing SOC stock in the whole soil layer in 0–35 cm. This phenomenon was explained by Kan et al. (2020), who reported that macro-aggregates played a key role in enhancing SOC accumulation, as more macro-aggregates under no-tillage enhanced C conversion from straw input, resulting in greater SOC stocks (0–30 cm layer) under no-tillage.

However, from the perspective of SOC distribution in different soil layers, no-tillage treatment only increased SOC content in soil surface layer (0–10 cm). The result was similar with Wang et al. (2018a), who indicated that the interactive effects of the residue at the soil surface under no-tillage management and the absence of soil disturbance result in the increases of SOC content to be limited to the soil surface. The SOC content under ploughing was significantly greater than that under no-tillage and subsoiling in the soil subsurface (10–20 and 20–35 cm), which may be related to the crop residues being ploughed into the soil of subsurface. Subsoiling significantly increased SOC content at 0–10 and 35–50 cm soil depths compared to ploughing, which can be explained by the characteristics of subsoiling. The reduction of soil disturbance during subsoiling resulted in the returned crop residues to cover most of the soil surface. In addition, subsoiling could break up the compacted hardpan layer and promote crop root growth, therefore, increasing the production of crop root litter and root exudates, which contributed to the increasing of SOM in the subsoil (Cai et al., 2014; Feng et al., 2018; Peng & Don, 2013).

### 4.2 Long-term fertilisation and tillage impact soil labile organic C fractions on CMI

The changes in the trends of soil labile organic C fractions (ROC, DOC, MBC and POC) were similar under all treatments. For fertilisation, the contents of soil labile organic C fractions were markedly greater under balanced fertilisation than that under conventional fertilisation and low fertilisation in the top soil (0–10 cm). That was primarily due to the greater C inputs under balanced fertilisation. Crop residues provide substrates for soil microorganisms and contribute to the accumulation of labile C (Jharna et al., 2018). Ding et al. (2012) also found that labile C levels were greater in fertilisation systems with greater C input. Considering all soil layers, the contents of soil labile organic C fractions in balanced fertilisation and conventional fertilisation were both greater than those in low fertilisation. This was due to the fact that low fertilisation had less crop residues, resulted in smaller soil microbial activity, thus decreasing the contents of soil labile organic C. For the tillage effect, due to the severe disturbance of soil, ploughing weakened the physical protection of SOC, exposed the protected organic matter to microbial decomposition, and accelerated mineralisation of labile organic matter in newly turned topsoil, thereby increasing the loss of soil labile C in topsoil (Awale et al., 2013; Chen et al., 2009). In contrast, the lesser soil disturbance under no-tillage and subsoiling...
contributed to greater levels of soil labile C contents at the 0–10 cm depth. Liu et al. (2014) reported that the distribution of soil labile organic C may be related to the placement of crop residues. Crop residues covering the soil surface are result in the increase of soil labile organic C at the 0–10 cm depth under no-tillage and subsoiling. Tillage caused the burial of crop residues, which led to the greater contents of soil labile organic C at a depth of 10–50 cm under ploughing compared with no-tillage. In addition, the contents of soil labile organic C fractions in deep soil (35–50 cm) were markedly greater in subsoiling compared to those in no-tillage and ploughing. This can be attributed to two factors. First, subsoiling increased the soil labile organic C by enhancing the microbial activity due to the improvement of soil structure of the deeper soil layer (He et al., 2019). Second, subsoiling increased root residues and exudates, which contributed to the soil labile organic C fractions (Hou et al., 2012).

CMI evaluates the relative potential of different management strategies to improve the soil quality. A larger CMI value indicates that the soil system is being rehabilitated, improved and sustained (Blair et al., 1995). In this study, fertilisation and tillage had significant impacts on CMI (Table 3). Balanced fertilisation strongly improved the CMI value compared to low fertilisation and conventional fertilisation, indicating that balanced fertilisation was beneficial for soil health development. Simultaneously, no-tillage and subsoiling markedly increased the value of CMI compared to ploughing at 0–10 cm depth. This was due to the fact that no-tillage and subsoiling reduced soil disturbance, leading to the greater content and labile of SOC at topsoil, thus improving soil quality at 0–10 cm depth (Ali et al., 2018). In addition, subsoiling increased soil porosity and improved soil structure of deeper soil (He, Zhang, et al., 2019), which contributed to the improvement of soil quality and increased CMI in 35–50 cm soil layer. Li, Wen, et al. (2018) reported that there was a positive linear correlation between CMI and carbon input. The CMI was calculated based on CPI and SOC lability index. Therefore, the greater crop residue C input and the lesser mineralisation of SOC are the reasons that the value of CMI in balanced fertilisation was larger than that under low fertilisation and conventional fertilisation, and CMI under no-tillage and subsoiling were larger than under ploughing.

4.3 Relationship between SOC pool and yield sustainability

Although fertilisation is an indispensable agricultural practice used to achieve large yields, a negative yield trend was observed under imbalanced use of inorganic fertilisation (Manna et al., 2005; Sun et al., 2019). We came to a similar conclusion that wheat yield in conventional fertilisation was significantly less than that under balanced fertilisation. In addition, balanced fertilisation also increased SYI compared to conventional fertilisation, suggested that balanced fertilisation with appropriate reductions in N and P fertiliser rates and supplemental K fertiliser had a positive benefit in maintaining soil productivity. This may be a result from the larger CMI value under balanced fertilisation (Table 5). Many studies have showed that no-tillage and subsoiling increase SOC sequestration, enhance soil fertility and water use efficiency, thereby strongly improving crop yield (Morrison et al., 2018; Xu et al., 2019). In this study, average wheat yields from 2008 to 2017 was increased by 6% and 9% under no-tillage and subsoiling, respectively, compared to ploughing. Furthermore, it is worth noting that the greatest SYI was found under subsoiling, indicating that subsoiling was superior to no-tillage and ploughing in maintaining crop production. This is because subsoiling could improve soil structure by loosening the soil and eliminating soil compaction, which facilitated root growth and development (He, Shi, & Yu, 2019). Wang et al. (2019) reported that subsoiling helps to increase soil available water capacity, improve the plant availability of water and nutrients from the subsoil, mitigate drought stress and thereby increasing crop yield.

In our study, SOC, soil labile C pool, CMI and input-C had significantly positive effects on wheat yield and SYI, which was confirmed by many studies (Li et al., 2016; Singh et al., 2018). From the results of path analysis, DOC and POC had direct effects on SYI due to their large direct path coefficients (0.47 and 0.26). DOC is produced from decomposition of soil organic matter mainly driven by soil microbes (Marschner & Bredow, 2002). POC is composed primarily of decomposing plant and animal residues (Wander et al., 1994). Kumar et al. (2018) reported that DOC and POC are important sources of plant nutrients as they are rapidly turned over and the nutrients released are easily absorbed and utilised by plants. SOC had indirect effect on SYI though DOC and POC, because the direct path coefficients (0.11) between SOC and SYI were less than their indirect path coefficients (0.36 by DOC, 0.16 by POC). This suggested that increasing the active components of SOC (especially DOC and POC) are important for maintaining crop production.

5 CONCLUSIONS

Our results showed that fertilisation and tillage practices strongly affected the SOC pool and crop productivity. SOC stock was increased by optimising fertilisation and
tillage, which was positively related to input-C and its stabilisation efficiency. Balanced fertilisation combined with conservation tillage (BF + NT and BF + ST treatments) produced greater SOC stock at 0–35 cm depth than other treatments. Meanwhile, balanced fertilisation, no-tillage and subsoiling were effective in increasing the contents of soil labile carbon fractions (ROC, DOC, MBC and POC) at 0–10 cm soil depth. Compared to ploughing, subsoiling also increased the contents of soil labile carbon fractions at 35–50 cm depth. Optimisation of tillage and fertilisation was beneficial to soil health development and the improvement of crop productivity due to the increase of SOC and labile organic C. Moreover, the effect of SOC contributed to SYI largely through indirect effects of DOC and POC. The greatest average yield of wheat and SYI were both recorded in BF + ST treatment. For SOC sequestration and sustainable productivity, balanced fertilisation combined with subsoiling appeared to be a sustainable management practice for increasing SOC storage, improving soil quality and maintaining crop production on the Loess Plateau in China.

ACKNOWLEDGEMENT
This work was supported by the Special Fund for Agro-scientific Research in the Public Interest of the Ministry of Agriculture, China (Grant no. 201503116).

CONFLICT OF INTEREST
No conflict of interest exits in the submission of this manuscript. All authors approved the manuscript for publication.

AUTHOR CONTRIBUTIONS
Xia Zhang: Conceptualization (equal); data curation (lead); investigation (lead); methodology (lead); resources (equal); validation (equal); visualization (lead); writing – original draft (lead). Mingle Wang: Data curation (supporting); investigation (supporting); methodology (supporting); writing – original draft (supporting). Dandan Zhang: Data curation (supporting); investigation (supporting); methodology (supporting); writing – original draft (supporting). Yulin Zhang: Conceptualization (equal); formal analysis (lead); methodology (equal); resources (lead); validation (equal); writing – review and editing (lead). Xudong Wang: Conceptualization (lead); formal analysis (lead); project administration (lead); supervision (lead); validation (lead); writing – review and editing (lead).

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

ORCID
Xudong Wang https://orcid.org/0000-0003-3988-2541

REFERENCES
Ali, K. K., Li, H. H., Lu, J. W., Li, X. X., K., Xue, B., & Yin, Z. Y. (2018). Long-term tillage and straw returning effects on organic C fractions and chemical composition of SOC in rice-rape cropping system. *Archives of Agronomy and Soil Science*, *65*(1), 125–137.

Awale, R., Chatterjee, A., & Franzen, D. (2013). Tillage and N-fertilizer influences on selected organic carbon fractions in a North Dakota silty clay soil. *Soil & Tillage Research*, *134*, 213–222.

Benbi, D. K., Brar, K., Toor, A. S., & Sharma, S. (2015). Sensitivity of labile soil organic carbon pools to long-term fertilizer, straw and manure management in rice-wheat system. *Pedosphere*, *25*(4), 534–545.

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. *Australian Journal of Agricultural Research*, *46*(7), 1459.

Bongiorno, G., Else, K. B., Oguejiofor, C. U., Meier, J., & Goede, R. D. (2018). Sensitivity of labile carbon fractions to tillage and organic matter management and their potential as comprehensive soil quality indicators across pedoclimatic conditions in Europe. *Ecological Indicators*, *99*, 35–50.

Cai, H. G., Ma, W., Zhang, X. Z., Ping, J. Q., Yan, X. G., Liu, J. Z., Yuan, J. C., Wang, L. C., & Ren, J. (2014). Effect of subsoil tillage depth on nutrient accumulation, root distribution, and grain yield in spring maize. *Crop Journal*, *2*, 297–307.

Camardella, C. A., & Elliott, E. T. (1992). Particulate soil organic-matter changes across a grassland cultivation sequence. *Soil Science Society of America Journal*, *56*, 777–783.

Carbonell-Bojollo, R., González-Sánchez, E. I., Repullo, R., 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 Research*, *53*(2), 113–124.

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 & Tillage Research*, *166*, 59–66.

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 Research*, *106*(1), 85–94.

Ding, G., Liu, X., Herbert, S., Novak, J., Amarasiriwardena, D., & Xing, B. (2006). Effect of cover crop management on soil organic matter. *Geoderma*, *130*(3–4), 229–239.

Ding, X. L., Han, X. Z., Liang, Y., Qiao, Y. F., Li, L. J., & Li, N. (2012). Changes in soil organic carbon pools after 10 years of continuous manuring combined with chemical fertilizer in a Molisol in China. *Soil & Tillage Research*, *122*, 36–41.

Doran, J. W., & Jones, A. J. (1996). *Methods for assessing soil quality* (pp. 123–141). Soil Science Society of America, Inc.

Duval, M. E., Galantini, J. A., Martinez, J. M., & Limbozzi, F. (2018). Labile soil organic carbon for assessing soil quality: Influence of management practices and edaphic conditions. *Catena*, *171*, 316–326.
Ellert, B. H., & Bettany, J. R. (1995). Calculation of organic matter and nutrients stored in soils under contrasting management regimes. *Canadian Journal of Soil Science, 75*, 529–538.

FAO/UNESCO. (1993). World Soil Resources: An explanatory note on the FAO World Soil Resources map at 1:25,000,000 Scale. In: W. S. R. (Ed.), *World Soil Resources Report* (p. 61). Rome: Food and Agriculture Organization of the United Nations.

Feng, X. M., Hao, Y. B., Latifmanesh, H., Lal, R., Cao, T. H., & FAO/UNESCO. (1993). *World Soil Resources: An explanatory note on the FAO World Soil Resources map at 1:25,000,000 Scale*. In: W. S. R. (Ed.), *World Soil Resources Report* (p. 61). Rome: Food and Agriculture Organization of the United Nations.

Feng, X. M., Hao, Y. B., Latifmanesh, H., Lal, R., Cao, T. H., Guo, J. R., Deng, A. X., Song, Z. W., & Zhang, W. J. (2018). Effects of subsoiling tillage on soil properties, maize root distribution, and grain yield on mollisols of Northeastern China. *Agronomy Journal, 110*(4), 1607–1615.

Ghosh, S., Wilson, B., Ghoshal, S., Senapati, N., & Mandal, B. (2012). Organic amendments influence soil quality and carbon sequestration in the Indo-Gangetic plains of India. *Agriculture, Ecosystems and Environment*, 156, 134–141.

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 Research*, 177, 134–144.

Gollany, H. T., & Polumsky, R. W. (2018). Simulating soil organic carbon responses to cropping intensity, tillage, and climate change in Pacific Northwest dryland. *Journal of Environmental Quality, 47*(4), 625–634.

Hamer, U., Potthast, K., & Makeschin, F. (2009). Urea fertilisation affected soil organic matter dynamics and microbial community structure in pasture soils of Southern Ecuador. *Applied Soil Ecology, 43*(2–3), 226–233.

He, J., Shi, Y., & Yu, Z. (2019). Subsoiling improves soil physical and microbial properties, and increases yield of winter wheat in the Huang-Huai-Hai Plain of China. *Soil & Tillage Research, 187*, 182–193.

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. *Journal of Cleaner Production, 234*, 297–305.

He, Y. T., He, X. H., Xu, M. G., Zhang, W. L., Yang, X. Y., & Huang, S. M. (2018). Long-term fertilization increases soil organic carbon and alters its chemical composition in three wheat-maize cropping sites across central and South China. *Soil & Tillage Research, 177*, 79–87.

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 and Management, 28*, 551–558.

Huang, M. X., Liang, T., Wang, L. Q., & Zhou, C. H. (2015). Effects of no-tillage systems on soil physical properties and carbon sequestration under long-term wheat–maize double cropping system. *Catena, 128*, 195–202.

Jat, H. S., Datta, A., Choudhary, M., Yadav, A. K., Choudhary, V., Sharma, P. C., Gathala, M. K., Jat, M. L., & Mcdonald, A. (2019). Effects of tillage, crop establishment and diversification on soil organic carbon, aggregation, associated aggregate carbon and productivity in cereal systems of semi-arid Northwest India. *Soil & Tillage Research, 190*, 128–138.

Jharna, R. S., Bhuminder, 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 Biology and Biochemistry, 116*, 22–38.

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. *Forest Ecology and Management, 256*, 30–36.

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), 622–636.

Kan, Z. R., Ma, S. T., Liu, Q. Y., Liu, B. Y., Virk, A. L., Qi, J. Y., Zhao, X., Lal, R., & Zhang, H. L. (2020). Carbon sequestration and mineralization in soil aggregates under long-term conservation tillage in the North China Plain. *Caten a, 188*, 104428.

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 Science Society of America Journal, 69*(4), 1078–1085.

Kumar, R., Naresh, R. K., Lal, M., Sachan, D. K., Mahajan, N. C., Singh, S., Singh, O., Kumar, R., & Chaudhary, V. (2018). Can conservation tillage and residue management effects on sensitivity of labile soil organic carbon fractions and soil organic carbon stocks in sub-tropical ecosystems: A review. *International Journal of Current Microbiology and Applied Sciences, 7*(11), 2063–2089.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science, 304*, 1623–1627.

Li, C. F., Yue, L. X., Kou, Z. 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 Research, 119*, 31–37.

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 Research, 175*, 281–290.

Li, J., Wu, X. P., Gebremikael, M. T., Wu, H. J., Cai, D. X., Wang, B. S., Li, B. G., Zhang, J. C., Li, Y. S., & Xi, J. L. (2018). Response of soil organic carbon fractions, microbial community composition and carbon mineralization to high-input fertilizer practices under an intensive agricultural system. *PLoS One, 13*(4), e0195144.

Li, J. H., Hou, Y. L., Zhang, S. X., Xu, D. H., & Knops, J. M. H. (2018). Fertilization with nitrogen and/or phosphorus lowers soil organic carbon sequestration in alpine meadows. *Land Degradation and Development, 29*, 1634–1641.

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 Research, 157*, 43–51.

Liu, C. A., & Zhou, L. M. (2017). Soil organic carbon sequestration and fertility response to newly-built terraces with organic manure and mineral fertilizer in a semi-arid environment. *Soil & Tillage Research, 172*, 39–47.

Liu, H. F., Zhang, J. Y., Ai, Z. M., Wu, Y., Xu, H. W., Li, Q., Xue, S., & Liu, G. B. (2018). 16-year fertilization changes the dynamics of soil oxidizable organic carbon fractions and the stability of soil organic carbon in soybean-corn agroecosystem. *Agriculture, Ecosystems & Environment, 265*, 320–330.
Sensitivity of soil carbon stocks and fractions to different land-use changes across Europe. *Geoderma*, 192(1), 189–201.

Prasad, J. V. N. S., Rao, C. S., Srinivasa, K., Jyothi, C. N., Venkateswarlu, B., Ramachandrappa, B. K., Dhanapal, G. N., Ravichandra, K., & Mishra, P. K. (2016). Effect of ten years of reduced tillage and recycling of organic matter on crop yields, soil organic carbon and its fractions in Alfisols of semi-arid tropics of southern India. *Soil & Tillage Research*, 156, 131–139.

Rahmati, M., Eskandari, I., Kousehloou, M., Feiziasl, V., Mahdavinia, G. R., Aliasgharzad, N., & Mckenzie, B. M. (2020). Changes in soil organic carbon fractions and residence time five years after implementing conventional and conservation tillage practices. *Soil & Tillage Research*, 200, 104632.

Rastogi, M., Singh, S., & Pathak, H. (2002). Emission of carbon dioxide from soil. *Current Science*, 82, 510–518.

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. *Scientific Reports*, 6(1), 19019.

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. *Journal of Environmental Management*, 223, 74–84.

Schimel, D. S. (1995). Terrestrial ecosystems and the carbon cycle. *Global Change Biology*, 1, 77–91.

Singh, S. R., Kundu, D. K., Dey, P., Singh, P., & Mahapatra, B. S. (2018). Effect of balanced fertilizers on soil quality and lentil yield in gangetic alluvial soils of India. *Journal of Agricultural Science*, 156, 1–16.

Sithole, N. J., Magwaza, L. S., & Thibaud, G. R. (2019). Long-term impact of no-till conservation agriculture and N-fertilizer on soil aggregate stability, infiltration and distribution of C in different size fractions. *Soil & Tillage Research*, 190, 147–156.

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, 90–97.

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 Research*, 171, 9–18.

Stewart, C. E., Roosendaal, D. L., Manter, D. K., Delgado, J. A., & Stephen, D. G. (2018). Interactions of stover and nitrogen management on soil microbial community and labile carbon under irrigated no-till corn. *Soil Science Society of America Journal*, 82(2), 323–331.

Sun, L., Wang, R., Li, J., Wang, Q., Lyu, W., Wang, X. L., Cheng, K., Mao, H. L., & Zhang, X. Q. (2019). Reasonable fertilization improves the conservation tillage benefit for soil water use and yield of rain-fed winter wheat: A case study from the Loess Plateau, China. *Field Crops Research*, 242, 107589.

Sun, L., Wang, S., Zhang, Y., Li, J., Wang, X., Wang, R., Lyu, W., Chen, 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, Ecosystems & Environment*, 251, 67–77.

Tang, H. M., Xiao, X. P., Tang, W. G., Li, C., Wang, K., Li, W. Y., Cheng, K. K., & Pan, X. C. (2018). Long-term effects of NPK fertilizers and organic manures on soil organic carbon and carbon management index under a double-cropping rice system in Southern China. *Communications in Soil Science and Plant Analysis*, 49(16), 1976–1989.
Tondello, G. (2007). Impacts of soil amendment history on nitrogen availability from manure and fertilizer. *Journal of Modern Optics*, 26(3), 357–371.

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 Biology and Biochemistry*, 19, 697–702.

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 Science*, 37(1), 29–38.

Wander, M. M., Traina, S. J., Stinner, B. R., & Peters, S. E. (1994). Organic and conventional management effects on biologically active soil organic matter pools. *Soil Science Society of America Journal*, 58, 1130–1139.

Wang, H., Bai, W., Han, W., Song, J. Q., & Lv, G. H. (2019). Effect of subsoiling on soil properties and winter wheat grain yield. *Soil Use and Management*, 35(4), 643–652.

Wang, H., Wang, S., Zhang, Y., Wang, X., Wang, R., & Li, J. (2018a). Tillage system change affects soil organic carbon storage and benefits land restoration in loess soil in North China. *Land Degradation and Development*, 29(9), 2880–2887.

Wang, S. L., Wang, H., Zhang, Y. H., Wang, R., Zhang, Y. J., Xu, Z. G., Jia, G. C., Wang, X. L., & Li, J. (2018b). The influence of rotational tillage on soil water storage, water use efficiency and maize yield in semi-arid areas under varied rainfall conditions. *Agricultural Water Management*, 203, 376–384.

Xie, J., Peng, B., Wang, R., Batbayar, J., Hoogmoed, M., Yang, Y., Zhang, S., Yang, X., & Sun, B. (2018). Responses of crop productivity and physical protection of organic carbon by macroaggregates to long-term fertilization of an Anthrosol. *European Journal of Soil Science*, 69(3), 555–567.

Xie, J. Y., Hou, M. M., Zhou, Y. T., Wang, R. J., Zhang, S. L., Yang, X. Y., & Sun, B. H. (2017). Carbon sequestration and mineralization of aggregate-associated carbon in an intensively cultivated Anthrosol in North China as affected by long term fertilization. *Geoderma*, 296, 1–9.

Xu, J., Han, H. F., Ning, T. Y., Li, Z. J., & Lal, R. (2019). Long-term effects of tillage and straw management on soil organic carbon, crop yield, and yield stability in a wheat-maize system. *Field Crops Research*, 233, 33–40.

Yan, X., Zhou, H., Zhu, Q. H., Wang, X. F., Zhang, Y. Z., Yu, X. C., & Peng, X. (2013). Carbon sequestration efficiency in paddy soil and upland soil under long-term fertilization in southern China. *Soil & Tillage Research*, 130, 42–51.

**How to cite this article:** Zhang, X., Wang, M., Zhang, D., Zhang, Y., & Wang, X. (2022). Increasing soil organic carbon pools and wheat yields by optimising tillage and fertilisation on the Loess Plateau in China. *European Journal of Soil Science*, 73(1), e13197. [https://doi.org/10.1111/ejss.13197](https://doi.org/10.1111/ejss.13197)