# Increasing soil organic carbon sequestration while closing the yield gap in Chinese wheat production

**Article** *in* Land Degradation & Development · November 2020

DOI: 10.1002/ldr.3747

Received: 8 December 2019 | Revised: 9 August 2020 | Accepted: 15 August 2020
DOI: 10.1002/ldr.3747

RESEARCH ARTICLE

WILEY

# Increasing soil organic carbon sequestration while closing the yield gap in Chinese wheat production

Yifan Guo | Mingyou Chen | Junxiao Pan | Yiwei Shang | Xingjie Wu | Zhenling Cui

Key Laboratory of Plant-Soil Interactions, Ministry of Education, Center for Resources, Environment and Food Security, China Agricultural University, Beijing, PR China

**Correspondence**
Zhenling Cui, Center for Resources, Environment and Food Security, China Agricultural University, Beijing 100193, PR China.
Email: cuizl@cau.edu.cn

**Funding information**
Qinghai Science and Technology Plan Project, Grant/Award Number: 2019-NK-A11; Taishan Scholarship Project of Shandong Province, Grant/Award Number: TS201712082

## Abstract

Managing soil organic carbon (SOC) to maximize crop yield is a vital strategy to feed the world's growing population. However, the low SOC contents in agricultural soils limits the maximization of wheat yield. Here, we used modeling and a long-term field experiment to determine whether improved crop management (IM) and an integrated procedure that combined IM with manure application (IMsoil) would close the yield gap while increasing SOC sequestration during wheat (*Triticum aestivum* L.) production in China. The yield of conventional farmers' practice (CM), operating with high fertilizer inputs, suboptimal management, and straw removal, was 5.3 Megagrams per hectare (Mg/ha), reaching 48% of yield potential (Yp, 11.0 Mg/ha) while reducing SOC sequestration during the year 2012–2019. The IM procedure with optimized density, planting dates, and nutrient management increased yield to 8.0 Mg/ha (i.e., 73% of Yp), and increased SOC sequestration. The IMsoil treatment further elevated wheat yield to 9.3 Mg/ha (i.e., 85% of Yp) by increasing spike number and pre-anthesis dry matter accumulation. The SOC sequestration in the IMsoil increased by 15.4 Mg C/ha at a rate of 2.20 Mg C ha-1 yr through large C inputs and high SOC transfer efficiencies compared with the beginning of this experiment. These results highlight the importance of combining optimized crop managements with soil amendment to close the yield gap with less fertilizer inputs while contributing to sustainable agriculture objectives.

KEYWORDS
dry matter accumulation, manure, population establishment, soil organic carbon stock, yield potential

## 1 | INTRODUCTION

Narrowing the gap between current realized yields and the yield potentials offers a realistic solution to meeting much of the global demand on existing agricultural lands (Cassman, 1999; van Ittersum et al., 2013). Yield potential assumes unconstrained crop growth and perfect management that avoid limitations from nutrient deficiencies and water stress, and incorporates effective control of weeds, pests, and diseases (Lobell, Cassman, & Field, 2009; van Ittersum & Rabbinge, 1997). Current development of sustainability seeks to close the yield gap by focusing on optimized field management practices, such as improved crop management, use of high-yield varieties, and optimizing water and fertilizer management (Lobell et al., 2009; Wang et al., 2017). However, these efforts are often hampered by soil constraints, such as land degradation and low soil organic carbon (SOC) content (Sanchez, 2010). Rebuilding resilient and productive soils is necessary for intensification of sustainable agriculture to maximize crop productivity while sequestrate more carbon to minimize climate change (Oldfield, Bradford, & Wood, 2019).

  

Soil organic carbon content and turnover are major indicators of agricultural soil quality and sustainability; SOC influences the physical, chemical, and biological parameters of agricultural soil (Bauer & Black, 1994; Larson & Pierce, 1991). Recycling organic materials (e.g., manure and straw) is the main win–win management practice for improving SOC content while reducing waste discharge into the environment (Chadwick et al., 2015; Gregorich, Carter, Angers, Monreal, & Ellert, 1994). Although many studies have reported a correlation between SOC and crop yield, agronomic responses to recycling organic materials to the soil have been inconsistent: Yields have reportedly increased (Akhtar et al., 2018; Xie et al., 2018), not responded (Baldi et al., 2018; Hijbeek et al., 2017), or even decreased (N'Dayegamiye, 2009). In practice, most farmers prefer to apply more chemical fertilizers to their fields, and not to recycle organic materials because recycling incurs uncertain yield responses and high labour costs. Strengthening the effects of recycling in maximizing crop yields would provide a crucial incentive to persuade local farmers to adopt this beneficial strategy across a wide area.

The wheat production system on the North China Plain (NCP) is a case in point. The NCP produces 67% of the national wheat crop (Wang et al., 2009), but the SOC content in the cropland is relatively low, and wheat production relies heavily on high or excessive chemical fertilizer inputs (Pan, 1999). For example, the SOC contents in some NCP intensive crop production areas are only 6.1–12.4 Mg/kg (Yan et al., 2016); the values are much lower than the range in Europe and the USA (25–40 Mg/kg; Fan, Christie, Zhang, & Zhang, 2010). Unfortunately, almost no animal manure has been used in wheat production over recent decades, although it is used in vegetable and fruit production (Zhang, Luo, Wu, Huang, & Christie, 2015). Instead, the typical fertilizer N rate applied by wheat farmers is ca. 300 kg N $ha^{-1}$ (Cui, 2005), although results from region-wide experiments have identified an optimal N rate of 187 kg N $ha^{-1}$ (Yin et al., 2019). Overuse of N fertilizer causes severe environmental pollution and land degradation, including increased greenhouse gas emissions (Zheng, Han, Huang, Wang, & Wang, 2004), soil acidification (Guo et al., 2010), and loss of soil microbial diversity (Wang, Liu, & Bai, 2018).

Recent agronomic innovations in crop and soil management show considerable promise for improving crop yields while greatly reducing harm to the environment (Cui, Yue, Wang, Zhang, & Chen, 2013; Khan, Chao, Waqas, Arp, & Zhu, 2013). For example, an integrated soil–crop system management procedure that optimized crop, water, and nutrient parameters was employed to produce high grain yields with fewer inputs (Chen et al., 2011; Zhang et al., 2011). Although the procedure is promising, wheat yields are still substantially lower than yield potentials. For example, wheat yield increased from 5.69 to 6.73 Mg/ha in 3734 on-farm trials over the last 10 years (Cui et al., 2018), but these yields were still below the yield potential (>9 Mg/ha) conducted across China (Liu et al., 2019; Liu, Wu, Chen, & Meng, 2016).

In this study, we postulated that the wheat yield gap could be narrowed further by using an integrated management procedure by combining optimized crop managements and soil carbon improvements. We conducted a 7-year field experiment to explore the effects of this integrated management procedure on agronomic outcome and soil quality. Specifically, we aimed to answer the following questions: (a) To what extent can an integrated management practice narrow the yield gap in Chinese wheat production? (b) Which agronomic and morphological traits contribute most to narrowing the yield gap? (c) How much carbon can be stored in soil under our integrated management practice?

## 2 | MATERIALS AND METHODS

### 2.1 | Site description and experimental design

Long-term field experiments were conducted in the period 2012–2019 at the Quzhou Experimental Station (36.9°N, 115.0°E), located in Quzhou County, Hebei Province, China. The average annual temperature was 13.2°C and the average annual precipitation was 500 mm. Detailed precipitation and mean temperature data for the seven study years are listed in Table 1. The experiments included two management systems: (a) Improved management with optimized crop and nutrient procedures (IM), and (b) integrated IM and soil amendment (IMsoil). Only single winter wheat was planted from October to early of June in next year and no crops were planted in the summer. The wheat was managed by using appropriate crop varieties and by optimizing sowing dates, plant densities, and split N fertilization procedures. Under the IMsoil treatment, 16 Mg/ha of air-dried cattle manure was applied annually. On average, the manure contained 259 g C $kg^{-1}$, 12.1 g N $kg^{-1}$, 14.2 g P $kg^{-1}$, and 11.4 g K $kg^{-1}$. The bulk density in the uppermost 30 cm of soil depth was 1.37 $Mg/cm^3$. Other parameters were as follows: SOC, 8.88 Mg/kg; total N, 1.0 Mg/kg; Olsen-P, 16 milligrams per kilogram (Mg/kg); available K, 179 Mg/kg; pH (in a 1:2.5 soil: water mixture), 8.3.

For comparison with our treatments, we selected a conventional management procedure (CM) from other long-term field experiments as a control. These other long-term experiments included five treatments, among which we only used the CM procedure in the current study. The CM plots were located <100 m away from our IM and IMsoil plots. The wheat of CM was planted with winter wheat/summer maize cropping system. Under CM, the wheat was grown following local farmers' practice (Table 2). The bulk density of the uppermost 30 cm of soil in the CM plots was 1.37 g $/cm^3$; other parameters were as follows: SOC, 7.83 Mg/kg; total N, 0.7 Mg/kg; Olsen-P, 5 Mg/kg; available K, 73 Mg/kg; pH (in a 1:2.5 soil: water mixture), 7.7. The management details of IM, IMsoil, and CM are listed in Table 2. The soils in the two experimental sites are classified as calcareous fluvo-aquic.

We used a completely randomized block-design with plot areas in the range 34–68 $m^2$. The basal fertilizers were evenly broadcast on the surface, and then incorporated into the soil before winter wheat sowing (early October). Supplemental urea was surface-applied manually at the stem elongation stage (early April), followed by wetting through irrigation or precipitation. The winter wheat was irrigated 90 mm on each occasion at the re-greening, shooting, and flowering stages. Threats such as weeds, pests, and diseases were controlled and no obvious stresses were observed.

**TABLE 1** Precipitation, monthly mean temperature, and monthly sunshine hours during wheat growing seasons (October–June) from 2012 to 2019 in the experiment field

| Month | Precipitation (mm) | | | | | | | Temperature (°C) | | | | | | | Sunshine hours (h) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 12/13 | 13/14 | 14/15 | 15/16 | 16/17 | 17/18 | 18/19 | 12/13 | 13/14 | 14/15 | 15/16 | 16/17 | 17/18 | 18/19 | 12/13 | 13/14 | 14/15 | 15/16 | 16/17 | 17/18 | 18/19 |
| October | 5.8 | 8.8 | 4.0 | 16.6 | 56.2 | 42.3 | 0.5 | 16.0 | 15.4 | 16.8 | 15.8 | 15.6 | 13.5 | 14.0 | 165 | 165 | 145 | 176 | 124 | 101 | 231 |
| November | 12.7 | 6.2 | 7.2 | 56.6 | 11.4 | 0.3 | 2.4 | 6.0 | 7.9 | 8.3 | 5.1 | 7.1 | 6.1 | 7.0 | 134 | 167 | 118 | 35 | 111 | 180 | 119 |
| December | 12.8 | 0.3 | 0 | 0 | 13.2 | 1.6 | 2.2 | −1.8 | 0.9 | 1.3 | 1.7 | 2.6 | −0.3 | −1.2 | 86 | 123 | 172 | 119 | 98 | 174 | 138 |
| January | 4.9 | 0 | 4.9 | 1.0 | 1.8 | 1.0 | 0.6 | −3.2 | 1.4 | 1.1 | −1.8 | −1.2 | −2.6 | −1.8 | 61 | 110 | 141 | 88 | 104 | 122 | 109 |
| February | 23.6 | 11.7 | 3.0 | 6.6 | 3.3 | 1.6 | 7.2 | 0.9 | 1.7 | 3.5 | 3.4 | 2.6 | 0.9 | 0.2 | 77 | 90 | 138 | 185 | 152 | 186 | 87 |
| March | 0.1 | 0 | 5.2 | 0 | 5.1 | 6.6 | 0 | 9.4 | 12.2 | 10.5 | 11.0 | 8.2 | 9.9 | 10.6 | 187 | 183 | 201 | 203 | 211 | 213 | 259 |
| April | 7.6 | 77.3 | 37.3 | 9.0 | 28.8 | 168.4 | 55.1 | 14.0 | 16.6 | 15.5 | 18.1 | 16.3 | 16.2 | 15.2 | 211 | 177 | 228 | 222 | 211 | 209 | 174 |
| May | 36.1 | 36.4 | 68.7 | 31.6 | 57.2 | 66.7 | 9.7 | 22.1 | 23.4 | 21.5 | 21.4 | 22.6 | 21.4 | 23.4 | 207 | 260 | 242 | 211 | 307 | 205 | 250 |
| June | 77.1 | 107.2 | 35.7 | 81.4 | 84.3 | 53.9 | 29.3 | 25.7 | 26.1 | 26.6 | 26.6 | 25.2 | 27.3 | 28.0 | 161 | 187 | 202 | 216 | 225 | 229 | 206 |
| Total | 180.7 | 247.9 | 166.0 | 202.8 | 261.3 | 342.4 | 107.0 | 89.1 | 105.6 | 105.0 | 101.2 | 99.0 | 92.5 | 95.5 | 1,288 | 1,462 | 1,588 | 1,454 | 1,544 | 1,619 | 1,574 |

## 2.2 | Sampling and laboratory procedures

At the harvest stage, plants from a randomly selected, $6m^2$ area in each plot were collected and thrashed manually to calculate the grain yield (with a standardized 14% moisture content). Before maturity, we counted the grains on each spike of 30 plants randomly collected in each replicate plot to calculate the number of grains per spike. To calculate the 1,000-grain weight, we randomly sampled three sets of 500 grains from each plot and weighed them. Grain and straw subsamples were sieved before measuring the N contents.

We counted the numbers of spikes at harvest and stems at the winter, stem elongation, and anthesis stages in one of the 1-$m^2$ length central rows of each replicate plot. Aboveground biomass was determined by sampling a 1-$m^2$ area located in the centre of each plot at the winter, stem elongation, anthesis, and harvest stages. The samples were oven-dried at 70°C to constant mass and then weighed. After the oven-dried subsamples had been screened through a 1-mm sieve and digested with $H_2SO_4$-$H_2O_2$, we determined plant N concentrations using the Kjeldahl method (Horowitz, 1970). To determine the dry matter (DM) weight of each tiller, we harvested 50 plants from each plot and separated each into the main stem (MS), tiller 1 (T1), tiller 2 (T2), and other tillers at the stem elongation stage, and into the MS, valid tillers (VT), and invalid tillers (IT) at the anthesis stage using the procedures of Kirby, Appleyard, and Fellowes (1985).

After the wheat harvest in 2019, we randomly collected soil samples at depths of 0–30 cm from each replicate plot; each sample consisted of five cores. An initial soil sample was taken in 2012 before the experiment was established. The samples were air-dried, ground, and sieved through a 0.25-mm mesh to remove crop residues. The processed samples were subjected to C/N analyses using a Vario Max CN analyzer (Elementar, Langenselbold, Germany). We determined soil bulk density in the 0–30 cm soil depth layer using the core method in the field. To measure the proportion of differently sized water-stable aggregates, we took additional soil samples from the 0–20 cm depth layer and sealed them in plastic boxes. These samples were carefully broken apart manually and screened through a 5-mm mesh. Crop residues in the specimens were removed with forceps, after which the processed samples were air-dried. Briefly, about 100 g of each soil sample was selected to calculate the proportions of differently sized water-stable aggregates using a wet-sieving procedure (Cambardella & Elliott, 1994). Four classes of water-stable aggregates were separated out: >2.000 mm, 0.250–2.000 mm, 0.053–0.250 mm, <0.053 mm (Six, Elliott, & Paustian, 2000). The soil specimens were dried at 65°C to constant mass and then weighed.

## 2.3 | Model development and validation

The Decision Support System for Agrotechnology Transfer (DSSAT) model is widely used to simulate crop growth and yield using

**TABLE 2** Practical crop managements including annual application rates for N, $P_2O_5$, $K_2O$, and manure, variety, density, sowing date, residue management, and soil tillage for CM, IM and IMsoil treatments in the long-term field treatment (2012–2019)

| Treatment | N (Mg/ha) | | $P_2O_5$ (Mg/ha) | $K_2O$ (Mg/ha) | Manure (Mg/ha) | Variety | Density (plant/ $m^2$) | Sowing date | Residue management | Soil tillage |
|---|---|---|---|---|---|---|---|---|---|---|
| | Basal | Topdressing | | | | | | | | |
| CM | 150 | 150 | 120 | 100 | 0 | Liangxing 99 | 490 | October 15 | Remove | Rotary tillage |
| IM | 100 | 120 | 120 | 100 | 0 | Liangxing 99 | 340 | October 5 | Return | Plough |
| IMsoil | 100 | 120 | 120 | 100 | 16,000 | Liangxing 99 | 340 | October 5 | Return | Plough |

Abbreviations: CM, conventional management; IM, improved management with optimized crop and nutrient procedures; IMsoil, integrated IM and soil amendment.

measured parameters, including daily weather, soil properties, crop genetic coefficients, and detailed crop management information (Jones et al., 2003). The model provided good simulations of phenological development for the calibration and evaluation years at Quzhou station (Figure 1). In our study, data on aboveground biomass in the periods 2012–2015 and 2015–2019 were used to calibrate and validate, respectively, the genetic coefficients of the DSSAT model (Figure 1a,b). After calibration, the model was evaluated for use at the Quzhou station in the period 2012–2019 (Figure 1c,d). The model provided good simulations of aboveground biomass (coefficient of determination [$R^2$] = 0.93, root mean square error [RMSE] = 1.53 Mg/ha, and normalized root mean square error [NRMSE] = 19.67). Simulated grain yields were in close agreement with our empirical observations ($R^2$ = 0.97, RMSE = 0.12 Mg/ha, NRMSE = 1.52).

## 2.4 | Calculations

Total SOC storage (Mg/ha) was calculated as follows:

$$\text{SOC stock} = \text{SOC} \times \text{BD} \times \text{D} \times 10$$

*Where:* SOC is the SOC concentration (Mg/kg), BD is soil bulk density (Mg/$m^3$), D is the depth of the soil layer (0.3 m), and 10 is a factor to adjust units.

The estimated total crop C input (Mg/ha) was calculated as follows:

$$\text{Total crop C input} = \sum_{i=1}^{7} (Xi \times R \times D + Si) \times \text{Ccrop},$$

*Where: i* is the number of years from 2012 to 2019, *Xi* is the aboveground biomass of crop in year *i*, *Si* is the amount of straw returned to field in year *i*, Ccrop is the organic C content residue (oven-dried basis, 399 g C $kg^{-1}$ for wheat and 444 g C $kg^{-1}$ for maize), *R* is the proportion of the annual rates of C input by roots accounting for the aboveground biomass (30% for wheat and 26% for maize), and *D* is the proportion of roots in the 0–30 cm soil depth layer (75.3% for wheat and 85.1% for maize). The remaining maize roots are calculated to estimate crop C input during maize growing seasons for CM treatment.

The estimated total manure C input (Mg C $ha^{-1}$) was calculated as follows:

$$\text{Total manure C input} = \sum_{i=1}^{7} Ai \times (1 - Wi) \times Ci,$$

*Where: i* is the number of years from 2012 to 2019, *Ai* is the amount of manure applied to field in year *i*, *Wi* is the moisture content of manure in year *i*, and *Ci* is the C content of manure in year *i*.

The C sequestration efficiency (%) was calculated as follows:

$$\text{C sequestration efficiency} = \frac{\text{SOC}_{\text{treatment}} - \text{SOC}_{\text{pre-soil}}}{\text{total crop C input} + \text{total manure C input}}$$

*Where:* $\text{SOC}_{\text{treatment}}$ and $\text{SOC}_{\text{pre-soil}}$ are the total SOC stocks at the end and at the start of the experiment, respectively.

The mean weight diameter (MWD, mm) is among the most reliable methods for evaluating the stability of soil aggregates (Schaller & Stockinger, 1953). The MWD of water-stable aggregates was calculated using the following formula:

$$\text{MWD} = \sum_{i=1}^{n} x_i w_i$$

*Where:* $x_i$ is the mean diameter of each size fraction (mm) and $w_i$ is the proportion of the total sample (WSA) in the corresponding size fraction (Kemper & Rosenau, 1986).

## 2.5 | Statistical analysis

The primary data were examined using Microsoft Excel spreadsheets. The correlation coefficients (*r*) between average wheat yield and spike number and stem number for pre-winter and stem elongation stages were analyzed. To identify significant long-term effects of CM, IM, and IMsoil treatments on SOC stock, SOC stock changes, crop C input, C sequestration efficiency, soil aggregates, grain yield, grain per spike, 1,000-grain weight, stem number, DM per tiller, aboveground biomass, and plant N concentrations, we used two-way analysis of variance with year as the primary factor and system treatment as the secondary factor. We used Fisher's LSD test to identify significant pairwise differences ($p < 0.05$) between means. SPSS software (SPSS Inc., Chicago, IL) was used for statistical calculations.

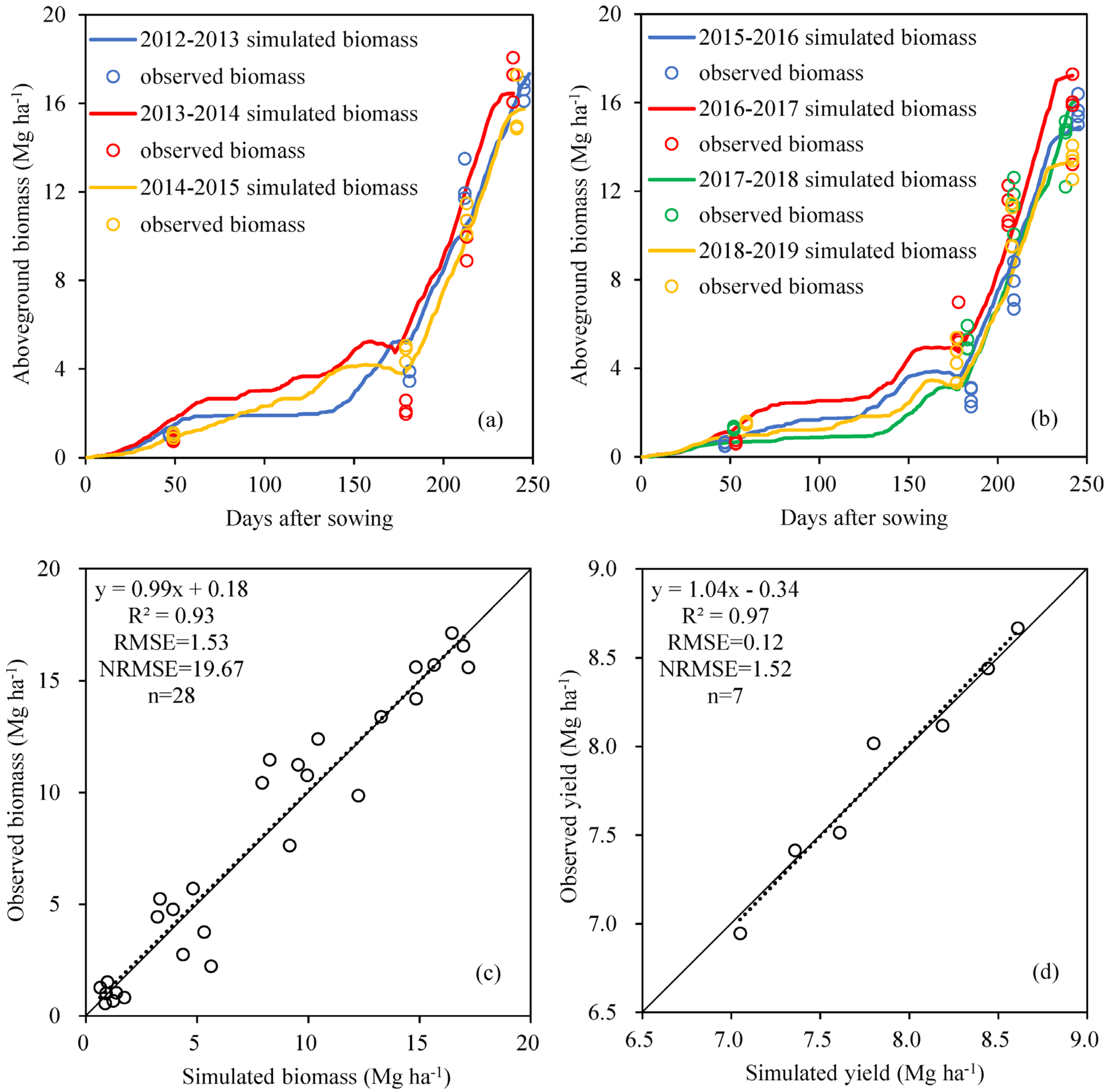


**FIGURE 1** DSSAT wheat model (a) calibration results from 2012 to 2015 and (b) validation results from 2015 to 2019 for wheat cultivar, Liangxing 99. Simulated (lines) and observed values (symbols) are shown for aboveground biomass. Comparison of calibrated versus observed (c) aboveground biomass and (d) grain yield. Line in (c) and (d) figures are 1 to 1 line. $R^2$, coefficient of determination; RMSE, root mean square error; NRMSE, normalized root mean square error. Data were collected from our experimental site [Colour figure can be viewed at wileyonlinelibrary.com]

## 3 | RESULTS

### 3.1 | Grain yield and simulated yield potential

The model provided good simulations of biomass accumulation years; simulated biomass and yields agreed well with observed values (Figure 1; see Methods). Based on 7 years of weather data (2012–2019), the DSSAT-modelled yield potential (Yp) of wheat averaged 11.0 Mg/ha (Table 3). Year-to-year variability in Yp was small at Quzhou (coefficient of variation [CV] = 4%), ranging from 10.4 to 11.6 Mg/ha. The wheat grain yield under CM averaged 5.3 Mg/ha (48% of Yp), ranging from 4.6 to 6.1 Mg/ha in the period 2012–2019. Under CM, the wheat yield was consistently lower at <60% of Yp, although there was year-to-year variability.

When IM practices were adopted, the wheat yield increased to 8.0 Mg/ha (73% of Yp, ranging from 66% in the period 2018–2019 to 84% in the period 2012–2013). Under IMsoil, the wheat yield further increased to 9.3 Mg/ha (85% of Yp, ranging from 7.7 to 10.3 Mg/ha,

**TABLE 3** The wheat biological potential yield simulated by the DSSAT model, experimental grain yield, and the achievement degree to yield potential for CM, IM, and IMsoil treatments from 2012 to 2019

| | Grain yield (Mg /ha) | | | |
|---|---|---|---|---|
| Year | Biological potential | CM | IM | IMsoil |
| 2012–2013 | 10.5 | 4.6 ± 0.3 (44%)c | 8.8 ± 0.1 (84%)b | 9.6 ± 0.1 (91%)a |
| 2013–2014 | 10.9 | 5.8 ± 0.7 (53%)c | 8.6 ± 0.1 (79%)b | 10.3 ± 0.4 (94%)a |
| 2014–2015 | 11.6 | 4.6 ± 0.7 (40%)c | 8.2 ± 1.0 (71%)b | 9.8 ± 0.2 (84%)a |
| 2015–2016 | 10.9 | 4.8 ± 0.1 (44%)c | 7.7 ± 0.4 (71%)b | 8.8 ± 0.5 (81%)a |
| 2016–2017 | 10.8 | 6.1 ± 0.9 (56%)c | 8.3 ± 0.9 (77%)b | 10.0 ± 0.6 (93%)a |
| 2017–2018 | 10.4 | 5.4 ± 0.3 (52%)b | 7.1 ± 0.7 (68%)a | 7.7 ± 0.4 (74%)a |
| 2018–2019 | 11.6 | 5.9 ± 0.4 (51%)c | 7.6 ± 0.4 (66%)b | 9.0 ± 0.6 (78%)a |
| Mean | 11.0 | 5.3 ± 0.8 (48%)c | 8.0 ± 0.8 (73%)b | 9.3 ± 0.9 (85%)a |

*Note*: Different letters denote significantly different means at $p < .05$ according to Fisher's LSD test. Abbreviations: CM, conventional management; IM, improved management with optimized crop and nutrient procedures; IMsoil, integrated IM and soil amendment.

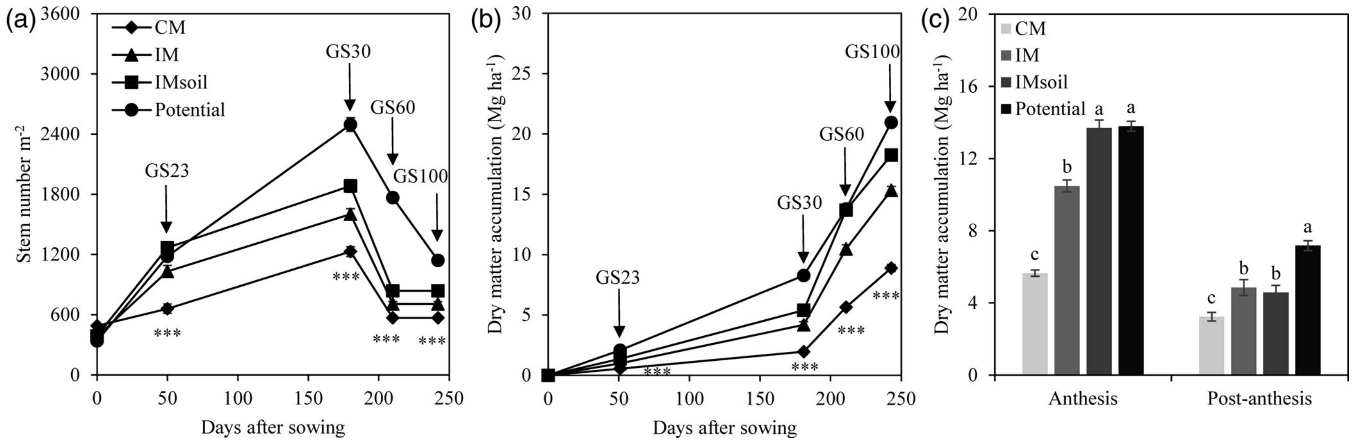


**FIGURE 2** Dynamics of (a) stem number, (b) dry matter accumulation under CM, IM, and IMsoil treatments and potential values; (c) anthesis and post-anthesis dry matter accumulation under CM, IM, and IMsoil treatments and potential values for 7-year period (2012–2019). CM, conventional management; IM, improved management with optimized crop and nutrient procedures; IMsoil, integrated IM and soil amendment; Potential, biological potential simulated by DSSAT model. GS23, GS30, GS60, and GS100 are the pre-winter, stem elongation, anthesis, and maturity stages, respectively. Values are means ± SE. *** Significant at $p < .001$. Different letters denote significantly different means at $p < .05$ according to Fisher's LSD test

that is, 74–94% of yield potential). The yield under IMsoil was 16 and 75% higher than under IM and CM, respectively. Over 7 years, the CV of grain yield decreased from 12% under CM to 8–10% under IM and IMsoil.

## 3.2 | Yield components and crop growth at different stages

In our field experiment, spike number, grain number, and 1,000-grain weight were significantly influenced by treatment, year, and their interaction (Table S1). Over all 7 years, the high yields under IM and IMsoil (compared to CM) were explained by high spike and grain numbers. The IMsoil treatment increased spike numbers by 18% relative to IM, but grain numbers were similar between treatments; the yield under IMsoil was 16% higher than under IM (Table 3). A close relationship between spike number and crop yield ($r$ = 0.81, $p < 0.001$; Table S2) was measured in all 7 years. Though the yield component of IMsoil was relatively high, there is still scope for improvement in spike numbers (as indicated by comparison with the simulated potential).

Over the 7 years, stem numbers under IMsoil were consistently higher than those under CM and IM through the entire wheat growing season (Figure 2a), although seed densities under IMsoil were similar to those under IM, and even more under CM. The pre-winter stem numbers under IMsoil were in the range 848–1924 $m^{-2}$, averaging 1,267 $m^{-2}$; this average value was 23 and 92% higher (significantly) than the averages under IM (mean 1,030 $m^{-2}$; range 544–1796 $m^{-2}$) and CM (mean 660 $m^{-2}$; range 419–1,052 $m^{-2}$), respectively. At the stem elongation stage, the stem numbers under IMsoil averaged 1883 $m^{-2}$, followed in rank order by 1,601 $m^{-2}$ under IM and 1,228 $m^{-2}$ under CM across all 7 years (Figure 2a). Positive linear relationships were found between pre-winter stem number and (a) spike number ($r$ = 0.80, $p < 0.001$) and (b) wheat yield ($r$ = 0.79, $p < 0.001$), and between total stem numbers at the stem elongation stage and (a) spike number ($r$ = 0.84, $p$ < 0.001) and (b) wheat yield ($r$ = 0.82, $p$ < 0.001) under all three treatments (Table S2). The stem numbers under the IMsoil treatment were 25 and 53% lower at the stem elongation and anthesis stages, respectively, than numbers predicted by the DSSAT model, but experimental pre-winter stem numbers slightly exceeded those predicted by the model.

Over 7 years, the individual tiller DM accumulation under IMsoil exceeded values under IM, largely due to elevated values obtained from tiller 2 (T2) at the stem elongation stage, and from valid tillers (VT) and invalid tillers (IT) at anthesis (Figure 3a,b). Specifically, under IMsoil, the DM accumulation of T2 (0.37 g per tiller) was significantly higher (54% higher) than under IM, but there was no significant difference between these two treatments in the DM accumulation of the main stem and tiller 1 (T1) at the stem elongation stage (Figure 3a). We detected no significant difference between these two treatments in the DM of the main stem at anthesis. The DM of VT and IT under IMsoil were 70 and 32% higher (significantly), respectively, than values under IM (Figure 3b).

Starting in the pre-winter stage, the DM accumulations under IM and IMsoil significantly exceeded accumulations under CM (Figure 2b). In the winter, stem elongation, anthesis, and harvest stages, the DM accumulations under IM averaged 1.0, 4.2, 10.5, and 15.3 Mg/ha, respectively; these values were 82%, 110%, 84%, and 72% higher, respectively, than those under CM treatment. The IMsoil treatment further increased DM accumulations to yet higher values, that is, 1.4, 5.4, 13.7, and 18.3 Mg/ha, respectively, at these four stages.

Differences in total DM accumulation among the three treatments occurred mainly before the anthesis stage; accumulations were similar across treatments after anthesis (3.2–4.9 Mg/ha; Figure 2c). The IM treatment improved pre-anthesis accumulation by 84% over the value obtained under CM (10.5 vs. 5.7 Mg/ha). Under IMsoil, DM accumulation increased to 13.7 Mg/ha (30% higher than the value under IM). The proportion of pre-anthesis DM accumulation under IMsoil amounted to 75% of the total; the respective proportions under IM and CM were 68% and 64%. No substantial difference was detected in pre-anthesis DM accumulation between the potential value and IMsoil treatment, but potential values for the post-anthesis period exceeded experimental values under all treatments.

The DM accumulation for IM and IMsoil treatments was affected by the variation of weather condition, which further affected the extent of yield gap closure. The relatively low temperature in the period of pre-winter in 2015 resulted in the lowest percentage of pre-anthesis DM accumulation with 49–57% of total biomass, comparing 58–85% of other years, and thus decreased grain yields in 2016. The sudden drop of temperature for a week in the period of stem elongation in 2018 resulted in the lowest post-anthesis DM accumulation as average 2.4–2.7 Mg/ha, comparing 3.0–8.0 Mg/ha of other years, and also decreased grain yields.

### 3.3 | Soil carbon sequestration and related soil quality

The initial SOC stock in 2012 in the 0–30 cm soil depth layer was 36.5 Mg/ha. Under IM, SOC sequestration over 7 years increased by 18% to reach 43.1 Mg/ha. Under IMsoil, values increased by 42% to 51.9 Mg/ha (Table 4). The annual C sequestration rates under IMsoil averaged 2.20 Mg ha$^{-1}$ yr$^{-1}$, a value 134% higher than the rate under IM (0.94 Mg ha$^{-1}$ yr$^{-1}$). In contrast, the SOC stock under CM decreased from 32.2 Mg/ha in 2012 to 29.7 Mg/ha in 2019.

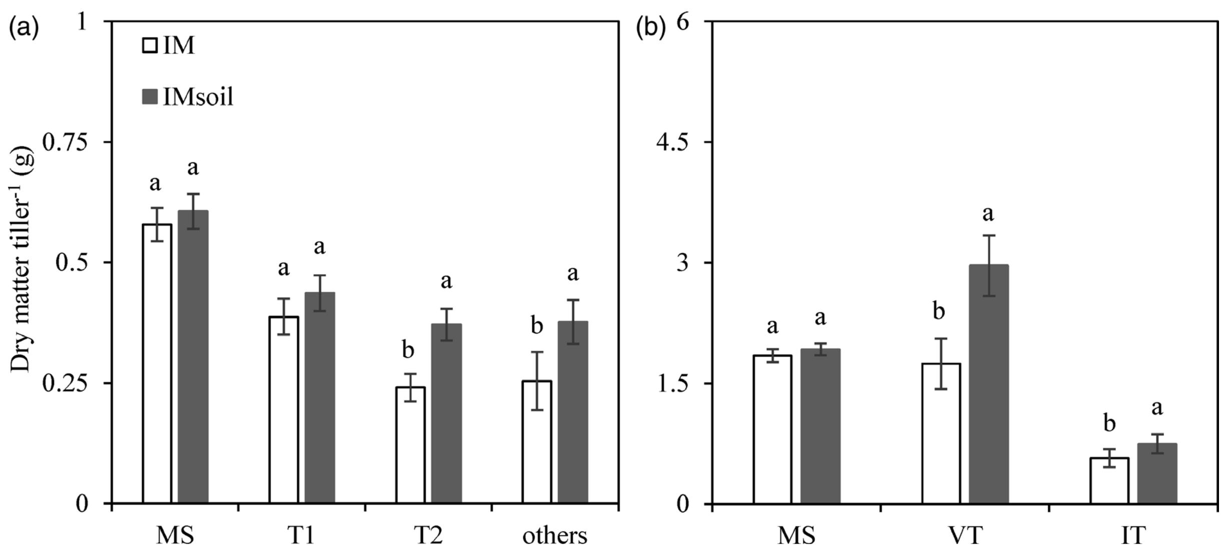


**FIGURE 3** Dry matter per tiller under IM and IMsoil treatments at the (a) stem elongation and (b) anthesis stage for 7-year period. IM, improved management with optimized crop and nutrient procedures; IMsoil, integrated IM and soil amendment; MS, main stem; T1, tiller 1; T2, tiller 2; others, other tillers; VT, valid tillers; IT, invalid tillers. Values are means ± SE. Different letters denote significantly different means at $p$ < .05 according to Fisher's LSD test

**TABLE 4** Soil organic carbon (SOC) stock changes in the period 2012–2019 in the 0–30 cm soil layer, crop C input, manure C input, and C sequestration efficiency in CM, IM, and IMsoil treatments

| | SOC stock in 2019 (Mg/ha) | SOC stock changes (Mg/ha) | Crop C Input (Mg/ha) | Manure C input (Mg/ha) | C sequestration efficiency (%) |
|---|---|---|---|---|---|
| CM | 29.7c | −2.5c | 18.1c | 0 | — |
| IM | 43.1b | 6.6b | 33.6b | 0 | 19.6b |
| IMsoil | 51.9a | 15.4a | 40.5a | 14.5 | 28.0a |

*Note*: The SOC stock at the start of the experiment was 32.2 Mg/ha for CM, and 36.5 Mg/ha for IM and IMsoil. Different letters denote significantly different means at $p < .05$ according to Fisher's LSD test.
Abbreviations: CM, conventional management; IM, improved management with optimized crop and nutrient procedures; IMsoil, integrated IM and soil amendment; SOC, soil organic carbon.

The total C input under IMsoil averaged 55.0 Mg/ha: 40.5 Mg/ha and 14.5 Mg/ha from crop residues and manure, respectively. The inputs were significantly higher than 33.6 Mg/ha under IM from high straw input and additional manure application. The C sequestration efficiency under IMsoil (28.0%) was substantially higher than that under IM (19.6%). The wheat grain yield increased linearly with the increases in SOC stock ($r = .93$, $p < .001$; Figure 4a).

The distribution of the soil water-stable aggregates was significantly influenced by the IMsoil treatment (Figure 4b). In the surface soil (0–20 cm depth), IMsoil significantly decreased the content of microaggregates (0.053–0.25 mm) and increased the contents of small macroaggregates (0.25–2.00 mm) and large macroaggregates (>2 mm), relative to the IM treatment. However, no significant effects were detected on the silt plus clay fraction (<0.053 mm; Figure 4b). The MWD was determined by the distribution proportions of all sizes of aggregates and reflected the stability of the aggregates. The MWD under the IMsoil treatment averaged 0.68, which was 42% higher than the value under IM (0.48).

## 4 | DISCUSSION

### 4.1 | Rapid increase in SOC sequestration

The maintenance and improvement of SOC sequestration have been used as measures to evaluate the effects of field management on soil quality and agricultural sustainability (Lal, 2004; Souza et al., 2014). In this study, a reduction in SOC sequestration after 7 years was observed under CM (Table 4). Farmers in the NCP remove aboveground crop residues for feeding their animals or fuel (Cui, Zhang, Chen, Dou, & Li, 2010; Wang et al., 2009), and this has resulted in low C inputs, leading to decreased SOC sequestration, even when the current SOC content was low. The estimated carbon input from remaining wheat and maize roots under CM was ca. 2.59 Mg C $ha^{-1}$ $yr^{-1}$ (Table 4), which was slightly above the carbon inputs required to maintain SOC stock stability (2.04 Mg C $ha^{-1}$ $yr^{-1}$) on the NCP (Fan et al., 2014).

The transformation of fresh organic materials to soil organic matter is very slow and inefficient; the process requires significant inputs over years or decades (Yan & Gong, 2010; Yang, Zhao, Huang, & Lv, 2015). The IM high wheat yielding treatment produced large crop carbon residues following straw return (ca. 4.80 Mg C $ha^{-1}$ $yr^{-1}$) and the SOC transfer efficiency from the crop residue was 19.6% (Table 4). This efficiency was a little higher than the current results with the 16% efficiency obtained under a wheat–soybean system on the Huang-Huai-Hai Plain, China (Hua, Wang, Guo, & Guo, 2014), the 14% efficiency obtained under a rice–wheat system in India (Majumder et al., 2008), and the 15.8–31.0% efficiency obtained in mild-temperate areas with mono-cropping systems (Zhang et al., 2010). Previous studies have reported a high SOC transfer efficiency (ca. 20%) under low precipitation and/or temperature conditions, such as those in Tibet (Yan, Cao, Liu, & Tao, 2007; Zhang et al., 2010). The soils in our study had low initial C contents and may, consequently, have had considerable potential for efficient storage of added C because they were below the C saturation level at the outset (Stewart, Paustian, Conant, Plante, & Six, 2008).

When manure was applied annually under IMsoil, SOC sequestration increased over 7 years by 8.8 Mg/ha above the sequestration value under IM (Table 4). These findings are supported by previous studies, showing that long-term application of manure combined with chemical fertilizers significantly increases SOC sequestration (Chaudhary, Dheri, & Brar, 2017; Zhu et al., 2007). Specifically, high SOC sequestration was explained by large carbon inputs and high SOC transfer efficiency (Table 4). Under IMsoil, the manure carbon input was 14.5 Mg/ha, and the high wheat yield produced a 21% increase in large crop carbon residue following straw return. On the other hand, manure application significantly increased the SOC sequestration transfer efficiency. Other studies demonstrated that manure applied in the field promoted microorganism activity and biomass carbon circulation, thereby increasing SOC sequestration (Fan et al., 2014; Haynes & Naidu, 1998; Nardi, Morari, Berti, Tosoni, & Giardini, 2004).

In our long-term field experiment, the proportion of large macroaggregates (>2.00 mm) and small macroaggregates (0.25–2.00 mm) was significantly increased by the IMsoil treatment compared with the IM treatment (Figure 4b). The higher proportion of macroaggregates may be explained by increases in the numbers of organic matter-filled pores in these aggregates (due to the elevation in SOC content following manure application); these pores serve as binding agents (Zhuang, McCarthy, Perfect, Mayer, & Jastrow, 2008).

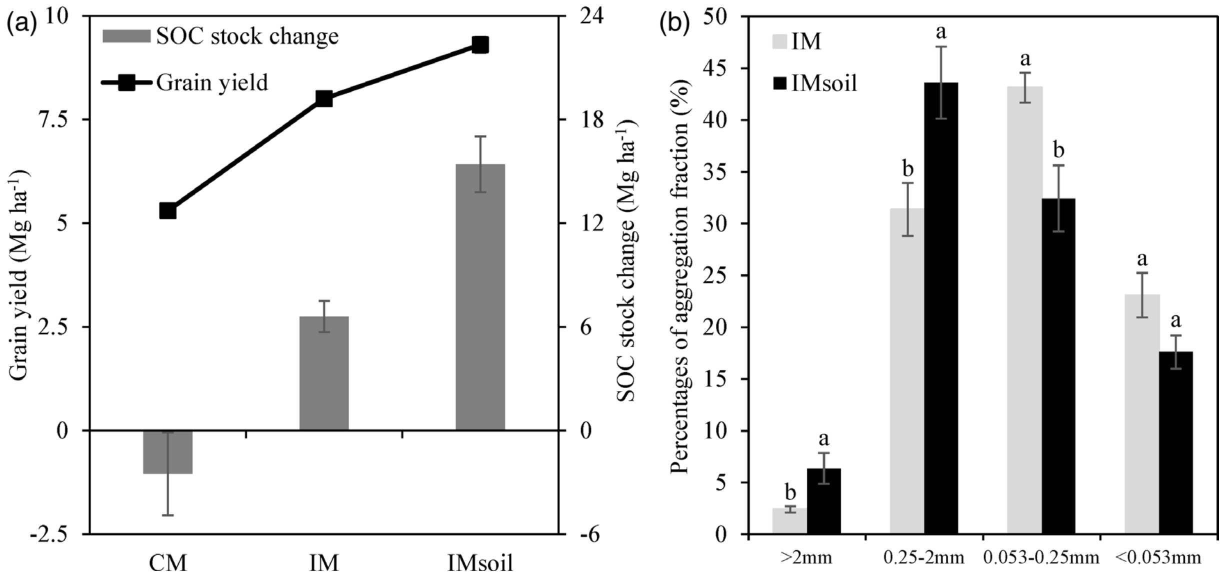


**FIGURE 4** (a) Grain yield and soil organic carbon (SOC) stock changes in the 0–30 cm soil layer in CM, IM, and IMsoil treatments, (b) soil water-stable aggregate distributions in the 0–20 cm soil layer under IM and IMsoil treatments in the period 2012–2019. SOC, soil organic carbon; CM, conventional management; IM, improved management with optimized crop and nutrient procedures; IMsoil, integrated IM and soil amendment. Values are means ± SE. Different letters denote significantly different means at $p < .05$ according to Fisher's LSD test

Furthermore, there was a significant increase in the MWD of water-stable aggregates under IMsoil. These results suggest that long-term manure addition had a positive influence on soil aggregate formation and MWD values, which were crucial for improving soil structure and providing physical protection for SOC (Shirani, Hajabbasi, Afyuni, & Hemmat, 2002; Six et al., 2000; Su, Wang, Suo, Zhang, & Du, 2006; Udom & Ogunwole, 2015).

## 4.2 | Closing the yield gap

The wheat yield under CM was still low with 5.3 Mg/ha and 48% of Yp, although wheat yield increased for over 7 years (Table 3), partly due to increasing mechanized efficiency. These yields under CM treatment are typical and similar to the national averages in China (FAO, 2017). In practice, most farmers on the NCP employ suboptimal crop management procedures, such as delayed sowing, inappropriate fertilizer practices, and aboveground residue removal (except for crop stubble), which in combination with poor soil quality may account for the large yield gap. Our optimized practices integrated a series of optimal cropping strategies to close yield gap, including appropriate sowing dates and densities, and advanced nutrient management based on local environments (Chen et al., 2014; Cui et al., 2018). For example, the proportion of N applied during each period was calculated according to a wheat crop N demand curve, with the larger amount of N fertilizer applied during rapid growth stage. As expected, wheat yield improved under IM, reaching 8.0 Mg/ha with 73% of Yp (Table 3). IM represents a large step forward, but the wheat yield was still lower than 80% of Yp; 80% is the expected attainable yield taking into account stagnation at regional to national scales due to diminishing returns from further investment in yield-enhancing technologies and inputs (Cassman, Dobermann, Walters, & Yang, 2003; Lobell et al., 2009).

The IMsoil treatment achieved a high yield of 9.3 Mg/ha (85% of Yp; Table 3). This yield was similar to the national highest yield records during the period 2005–2015 when wheat yields were maximized, generally by selecting favorable weather and soil condition and using very large inputs of water and nutrients (Liu et al., 2016). In our study, high yields were achieved over 7 years in the same field. In a single year, high yields may result simply from random processes, but the long-term performance that we achieved indicates that our integrated management procedure sustained wheat productivity. The wheat yields we achieved were comparable to a yield of 9.5 Mg/ha in Germany under the most advanced conditions and agronomic measures applied worldwide (van Wart, Grassini, & Cassman, 2013). Clearly, our integrated management practice is optimal for future sustainable wheat production in China in terms of both high yield and soil quality.

## 4.3 | Increasing stem numbers and pre-anthesis biomass

The high wheat yield under IMsoil can be explained by the increased spike numbers and pre-anthesis biomass (in comparison with other treatments). Previous studies showed that high spike numbers were closely related to increased wheat yield on the NCP (Guan et al., 2015; Lu et al., 2015a). A reduction in yield associated with low spike numbers cannot be offset by increases in other yield components on the NCP (Lu et al., 2015a). For instance, Lu et al. (2016)

reported that a high-yield group (>8.5 Mg/ha) had higher spike numbers than lower yield groups (<7.0 Mg/ha and 7.0–8.5 Mg/ha); pre-winter stem numbers were related to yield grouping in this manner.

The IMsoil treatment improved population development and individual tiller DM accumulation (Figures 2a and 3), which together contributed most to spike number. On the NCP, increased pre-winter stem number and reduced tiller mortality at anthesis were critical for wheat production. Pre-winter stem number was positively related to spike number and crop yield (Table S2). Most farmers on the NCP prefer to use high sowing density to produce sufficient number of pre-winter stems; this practice may depress stem population growth in spring, thereby reducing spike numbers (Wang et al., 2009).

Tiller mortality is elevated from stem elongation to anthesis when the densities of basic stems and unproductive tillers (other tillers) are high (Alzueta, Abeledo, Mignone, & Miralles, 2012; Berry, Spink, Foulkes, & Wade, 2003). An enhancing effect of manure on tiller production was also reported by Mason and Spaner (2006). Our results highlighted that high plant N concentrations for the IMsoil in the period from stem elongation to anthesis (Table S3), ensuring rapid accumulation of DM and reductions in the mortality of late-initiated tillers, particularly valid tillers, which had elevated levels of DM accumulation (Figures 2b and 3b).

High wheat yield depends on high total DM accumulation (Rhoads & Stanley, 1981). However, the relative importance of pre- versus post-anthesis DM accumulation for grain yield remains an unresolved issue (Papakosta & Gagianas, 1991; Ye et al., 2011). The differences in DM accumulation among the CM, IM, and IMsoil treatments mainly occurred pre-anthesis, particularly in the period from stem elongation to anthesis (Figure 2b,c). This finding is not concordant with other investigations, showing that wheat grain yield has a positive relationship with DM accumulation after anthesis (Duan et al., 2018; Foulkes et al., 2007; Zhang, Turner, & Poole, 2012). This difference is explained that the grain-filling period in the NCP is short from the beginning of May to the 10th of June, and the dry/hot weather during the post-anthesis period accelerates the maturity (Papakosta & Gagianas, 1991; Sun, Liu, Zhang, Shen, & Zhang, 2006).

### 4.4 | Uncertain analysis

Our analysis also identified gaps in data and knowledge. It would be difficult to identify possible underlying mechanisms that may explain how the IMsoil treatment closed the yield gap. Nutrients derived from chemical fertilizers are instantly available to plants, but manure releases nutrients slowly, thereby increasing the sizes of C and N pools and achieving a better match between nutrient supply and wheat demands, especially during the critical growing period (Seufert, Ramankutty, & Foley, 2012; Six, Conant, Paul, & Paustian, 2002). Surface soil temperature is increased by manure addition (Naeini & Cook, 2000), which is important for wheat population establishment and early seedling growth (Deguchi, Kawamoto, Tanaka, Fushimi, & Uozumi, 2009; Lu et al., 2015b). Other possible underlying mechanisms include improvements in available water capacity, soil structure, and other physical properties (Darwish, Persaud, & Martens, 1995). Although the soil type was the same as calcareous fluvo-aquic between CM and IM (IMsoil) treatments, the supply of nutrients was slightly different because of a certain gap in the initial soil physical and chemical properties, which may affect the experimental results. More rigorous experiments will be added in the future. In addition, there is a lack of information reported on the key chemicals (e.g., Total and labile C contents, ammonium content, pH) and physical characteristics of the manure (dry matter content, viscosity), which hampers the identification of mechanisms with manure addition for closing yield gaps.

## 5 | CONCLUSIONS

We showed that the long-term use of a procedure that coupled optimized practices with manure application improved wheat productivity, SOC stocks, and formation of soil water-stable aggregates. When conventional management (CM) was adopted, the yield gap was large and SOC stock in the 0–30 cm soil depth layer was reduced; when managements were improved (IM), the yield and SOC stock were partly increased; when IM and soil amendment were integrated (IMsoil), the yield gap was further closed, and SOC stock and the formation of soil water-stable aggregates were improved. More importantly, yield improvement under IMsoil resulted mainly from increases in spike number and pre-anthesis DM accumulation. Our IMsoil procedure provides an opportunity for closing the yield gap while reducing fertilizer inputs and improving soil quality during wheat production. These advances would be promoted by providing guidance, technologies, and incentives that are readily adopted by farmers, not only in China, but also in other countries with similar environmental and farming conditions.

### ACKNOWLEDGMENTS

The current work was funded by the Qinghai Science and Technology Plan Project (2019-NK-A11) and the Taishan Scholarship Project of Shandong Province (TS201712082).

### CONFLICT OF INTEREST

The authors declare no conflicts of interest.

### DATA AVAILABILITY STATEMENT

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

### ORCID

*Yifan Guo* https://orcid.org/0000-0003-2600-5005
*Junxiao Pan* https://orcid.org/0000-0003-0416-3336

### REFERENCES

Akhtar, K., Wang, W. Y., Ren, G. X., Khan, A., Feng, Y. Z., & Yang, G. H. (2018). Changes in soil enzymes, soil properties, and maize crop productivity under wheat straw mulching in Guanzhong, China. *Soil and*

*Tillage Research*, *182*, 94–102. https://doi.org/10.1016/j.still.2018.05.007

Alzueta, I., Abeledo, L. G., Mignone, C. M., & Miralles, D. J. (2012). Differences between wheat and barley in leaf and tillering coordination under contrasting nitrogen and sulfur conditions. *European Journal of Agronomy*, *41*, 92–102. https://doi.org/10.1016/j.eja.2012.04.002

Baldi, E., Cavani, L., Margon, A., Quartieri, M., Sorrenti, G., Marzadori, C., & Toselli, M. (2018). Effect of compost application on the dynamics of carbon in a nectarine orchard ecosystem. *Science of the Total Environment*, *637-638*, 918–925. https://doi.org/10.1016/j.scitotenv.2018.05.093

Bauer, A., & Black, A. L. (1994). Quantification of the effect of soil organic-matter content on soil productivity. *Soil Science Society of America Journal*, *58*, 185–193. https://doi.org/10.2136/sssaj1994.03615995005800010027x

Berry, P. M., Spink, J. H., Foulkes, M. J., & Wade, A. (2003). Quantifying the contributions and losses of dry matter from non-surviving shoots in four cultivars of winter wheat. *Field Crops Research*, *80*, 111–121. https://doi.org/10.1016/S0378-4290(02)00174-0

Cambardella, C. A., & Elliott, E. T. (1994). Carbon and nitrogen dynamics of soil organic matter fractions from cultivated grassland soils. *Soil Science Society of America Journal*, *58*, 123–130. https://doi.org/10.2136/sssaj1994.03615995005800010017x

Cassman, K. G. (1999). Ecological intensification of cereal production systems: Yield potential, soil quality, and precision agriculture. *Proceedings of the National Academy of Sciences of the United States of America*, *96*, 5952–5959. https://doi.org/10.1073/pnas.96.11.5952

Cassman, K. G., Dobermann, A., Walters, D. T., & Yang, H. (2003). Meeting cereal demand while protecting natural resources and improving environmental quality. *Annual Review of Environment and Resources*, *28*, 315–358. https://doi.org/10.1146/annurev.energy.28.040202.122858

Chadwick, D., Jia, W., Tong, Y. A., Yu, G. H., Shen, Q. R., & Chen, Q. (2015). Improving manure nutrient management towards sustainable agricultural intensification in China. *Agriculture, Ecosystems & Environment*, *209*, 34–46. https://doi.org/10.1016/j.agee.2015.03.025

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 and Tillage Research*, *166*, 59–66. https://doi.org/10.1016/j.still.2016.10.005

Chen, X. P., Cui, Z. L., Fan, M. S., Vitousek, P., Zhao, M., Ma, W. Q., … Zhang, F. S. (2014). Producing more grain with lower environmental costs. *Nature*, *514*, 486–489. https://doi.org/10.1038/nature13609

Chen, X. P., Cui, Z. L., Vitousek, P. M., Cassman, K. G., Matson, P. A., Bai, J. S., … Zhang, F. S. (2011). Integrated soil-crop system management for food security. *Proceedings of the National Academy of Sciences of the United States of America*, *108*, 6399–6404. https://doi.org/10.1073/pnas.1101419108

Cui, Z. L. (2005). *Optimization of the nitrogen fertilizer management for a winter wheat-summer maize rotation system in the North China Plain-from field to regional scale*. (PhD dissertation). China Agricultural University, Beijing. (in Chinese)

Cui, Z. L., Yue, S. C., Wang, G. L., Zhang, F. S., & Chen, X. P. (2013). In-season root-zone N management for mitigating greenhouse gas emission and reactive N losses in intensive wheat production. *Environmental Science & Technology*, *47*, 6015–6022. https://doi.org/10.1021/es4003026

Cui, Z. L., Zhang, F. S., Chen, X. P., Dou, Z. X., & Li, J. L. (2010). In-season nitrogen management strategy for winter wheat: Maximizing yields, minimizing environmental impact in an over-fertilization context. *Field Crops Research*, *116*, 140–146. https://doi.org/10.1016/j.fcr.2009.12.004

Cui, Z. L., Zhang, H. Y., Chen, X. P., Zhang, C. C., Ma, W. Q., Huang, C. D., … Dou, Z. X. (2018). Pursuing sustainable productivity with millions of smallholder farmers. *Nature*, *555*, 363–366. https://doi.org/10.1038/nature25785

Darwish, O. H., Persaud, N., & Martens, D. C. (1995). Effect of long-term application of animal manure on physical properties of three soils. *Plant and Soil*, *176*, 289–295. https://doi.org/10.1007/BF00011793

Deguchi, S., Kawamoto, H., Tanaka, O., Fushimi, A., & Uozumi, S. (2009). Compost application increases the soil temperature on bare andosol in a cool climate region. *Soil Science and Plant Nutrition*, *55*, 778–782. https://doi.org/10.1111/j.1747-0765.2009.00420.x

Duan, J. Z., Wu, Y. P., Zhou, Y., Ren, X. X., Shao, Y. H., Feng, W., … Guo, T. C. (2018). Approach to higher wheat yield in the Huang-Huai Plain: Improving post-anthesis productivity to increase harvest index. *Frontiers in Plant Science*, *9*(1457). https://doi.org/10.3389/fpls.2018.01457

Fan, J. L., Ding, W. X., Xiang, J., Qin, S. W., Zhang, J. B., & Ziadi, N. (2014). Carbon sequestration in an intensively cultivated sandy loam soil in the North China Plain as affected by compost and inorganic fertilizer application. *Geoderma*, *230-231*, 22–28. https://doi.org/10.1016/j.geoderma.2014.03.027

Fan, M. S., Christie, P., Zhang, W. F., & Zhang, F. S. (2010). Crop productivity, fertilizer use, and soil quality in China. In *Advances in Soil Science: Food Security and Soil Quality* (pp. 87–107). Boca Raton, FL: CRC Press.

Food and Agriculture Organization of the United Nations (FAO) (2017). FAOSTAT-Agriculture Database. Retrieved 9 October 2019 from http://www.fao.org/faostat/en/#data/QC

Foulkes, M. J., Snape, J. W., Shearman, V. J., Reynolds, M. P., Gaju, O., & Sylvester-Bradley, R. (2007). Genetic progress in yield potential in wheat: Recent advances and future prospects. *The Journal of Agricultural Science*, *145*, 17–29. https://doi.org/10.1017/S0021859607006740

Gregorich, E. G., Carter, M. R., Angers, D. A., Monreal, C. M., & Ellert, B. H. (1994). Towards a minimum data set to assess soil organic matter quality in agricultural soils. *Canadian Journal of Soil Science*, *74*, 367–385. https://doi.org/10.4141/cjss94-051

Guan, D. H., Zhang, Y. S., Al-Kaisi, M. M., Wang, Q. Y., Zhang, M. C., & Li, Z. H. (2015). Tillage practices effect on root distribution and water use efficiency of winter wheat under rain-fed condition in the North China Plain. *Soil and Tillage Research*, *146*, 286–295. https://doi.org/10.1016/j.still.2014.09.016

Guo, J. H., Liu, X. J., Zhang, Y., Shen, J. L., Han, W. X., Zhang, W. F., … Zhang, F. S. (2010). Significant acidification in major Chinese croplands. *Science*, *327*, 1008–1010. https://doi.org/10.1126/science.1182570

Haynes, R. J., & Naidu, R. (1998). Influence of lime, fertilizer and manure applications on soil organic matter content and soil physical conditions: A review. *Nutrient Cycling in Agroecosystems*, *51*, 123–137. https://doi.org/10.1023/A:1009738307837

Hijbeek, R., van Ittersum, M. K., ten Berge, H. F. M., Gort, G., Spiegel, H., & Whitmore, A. P. (2017). Do organic inputs matter: A meta-analysis of additional yield effects for arable crops in Europe. *Plant and Soil*, *411*, 293–303. https://doi.org/10.1007/s11104-016-3031-x

Horowitz, W. (1970). *Official methods of analysis* (11th ed., pp. 17–18). Washington, DC: AOAC.

Hua, K. K., Wang, D. Z., Guo, X. S., & Guo, Z. B. (2014). Carbon sequestration efficiency of organic amendments in a long-term experiment on a Vertisol in Huang-Huai-Hai Plain, China. *PLoS One*, *9*, e108594. https://doi.org/10.1371/journal.pone.0108594

Jones, J. W., Hoogenboom, G., Porter, C. H., Boote, K. J., Batchelor, W. D., Hunt, L. A., … Ritchie, J. T. (2003). The DSSAT cropping system model. *European Journal of Agronomy*, *18*, 235–265. https://doi.org/10.1016/S1161-0301(02)00107-7

Kemper, W. D., & Rosenau, R. C. (1986). Aggregate stability and size distribution. In *Methods of soil analysis, part 1. Physical and mineralogical* *methods: Agronomy monograph* (2nd ed., pp. 425–442). Madison: Soil Science Society of America.

Khan, S., Chao, C., Waqas, M., Arp, H. P. H., & Zhu, Y. G. (2013). Sewage sludge biochar influence upon rice (*Oryza sativa* L) yield, metal bioaccumulation and greenhouse gas emissions from acidic paddy soil. *Environmental Science & Technology*, *47*, 8624–8632. https://doi.org/10.1021/es400554x

Kirby, E. J. M., Appleyard, M., & Fellowes, G. (1985). Variation in development of wheat and barley in response to sowing date and variety. *The Journal of Agricultural Science*, *104*, 383–396. https://doi.org/10.1017/S0021859600044075

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. *Science*, *304*, 1623–1627. https://doi.org/10.1126/science.1097396

Larson, W. E., & Pierce, F. J. (1991). *Conservation and enhancement of soil quality*. In Evaluation for sustainable land management in the developing world: Proceedings of the international workshop on evaluation for sustainable land Management in the Developing World, Chiang Rai, Thailand. pp. 15–21.

Liu, B. H., Wu, L., Chen, X. P., & Meng, Q. F. (2016). Quantifying the potential yield and yield gap of Chinese wheat production. *Agronomy Journal*, *108*, 1890–1896. https://doi.org/10.2134/agronj2016.03.0147

Liu, Z. T., Yin, Y. L., Pan, J. X., Ying, H., Lu, D. J., Batchelor, W. D., … Cui, Z. L. (2019). Yield gap analysis of county level irrigated wheat in Hebei Province, China. *Agronomy Journal*, *111*, 2245–2254. https://doi.org/10.2134/agronj2018.12.0784

Lobell, D. B., Cassman, K. G., & Field, C. B. (2009). Crop yield gaps: Their importance, magnitudes, and causes. *Annual Review of Environment and Resources*, *34*, 179–204. https://doi.org/10.1146/annurev.environ.041008.093740

Lu, D. J., Lu, F. F., Pan, J. X., Cui, Z. L., Zou, C. Q., Chen, X. P., … Wang, Z. L. (2015a). The effects of cultivar and nitrogen management on wheat yield and nitrogen use efficiency in the North China Plain. *Field Crops Research*, *171*, 157–164. https://doi.org/10.1016/j.fcr.2014.10.012

Lu, D. J., Lu, F. F., Pan, J. X., Cui, Z. L., Zou, C. Q., Chen, X. P., … Wang, Z. L. (2015b). Manure limits wheat yield losses due to delayed seeding. *Agronomy Journal*, *107*, 2294–2302. https://doi.org/10.2134/agronj15.0008

Lu, D. J., Yue, S. C., Lu, F. F., Cui, Z. L., Liu, Z. H., Zou, C. Q., & Chen, X. P. (2016). Integrated crop-N system management to establish high wheat yield population. *Field Crops Research*, *191*, 66–74. https://doi.org/10.1016/j.fcr.2016.02.015

Majumder, B., Mandal, B., Bandyopadhyay, P. K., Gangopadhyay, A., Mani, P. K., Kundu, A. L., & Mazumdar, D. (2008). Organic amendments influence soil organic carbon pools and rice-wheat productivity. *Soil Science Society of America Journal*, *72*, 775–785. https://doi.org/10.2136/sssaj2006.0378

Mason, H. E., & Spaner, D. (2006). Competitive ability of wheat in conventional and organic management systems: A review of the literature. *Canadian Journal of Plant Science*, *86*, 333–343. https://doi.org/10.4141/P05-051

N'Dayegamiye, A. (2009). Soil properties and crop yields in response to mixed paper mill sludges, dairy cattle manure, and inorganic fertilizer application. *Agronomy Journal*, *101*, 826–835. https://doi.org/10.2134/agronj2008.0170x

Naeini, S. A. R. M., & Cook, H. F. (2000). Influence of municipal waste compost amendment on soil water and evaporation. *Communications in Soil Science and Plant Analysis*, *31*, 3147–3161. https://doi.org/10.1080/00103620009370657

Nardi, S., Morari, F., Berti, A., Tosoni, M., & Giardini, L. (2004). Soil organic matter properties after 40 years of different use of organic and mineral fertilisers. *European Journal of Agronomy*, *21*, 357–367. https://doi.org/10.1016/j.eja.2003.10.006

Oldfield, E. E., Bradford, M. A., & Wood, S. A. (2019). Global meta-analysis of the relationship between soil organic matter and crop yields. *The Soil*, *5*, 15–32. https://doi.org/10.5194/soil-5-15-2019

Pan, G. X. (1999). Study on carbon reservoir in soils of China. *Bulletin of Science and Technology*, *15*, 330–332 (in Chinese).

Papakosta, D. K., & Gagianas, A. A. (1991). Nitrogen and dry matter accumulation, remobilization, and losses for Mediterranean wheat during grain filling. *Agronomy Journal*, *83*, 864–870. https://doi.org/10.2134/agronj1991.00021962008300050018x

Rhoads, F. M., & Stanley, R. L. (1981). Fertilizer scheduling, yield, and nutrient uptake of irrigated corn. *Agronomy Journal*, *73*, 971–974. https://doi.org/10.2134/agronj1981.00021962007300060015x

Sanchez, P. A. (2010). Tripling crop yields in tropical Africa. *Nature Geoscience*, *3*, 299–300. https://doi.org/10.1038/ngeo853

Schaller, F. W., & Stockinger, K. R. (1953). A comparison of five methods for expressing aggregation data. *Soil Science Society of America Journal*, *17*, 310–345. https://doi.org/10.2136/sssaj1953.03615995001700040002x

Seufert, V., Ramankutty, N., & Foley, J. A. (2012). Comparing the yields of organic and conventional agriculture. *Nature*, *485*, 229–232. https://doi.org/10.1038/nature11069

Shirani, H., Hajabbasi, M. A., Afyuni, M., & Hemmat, A. (2002). Effects of farmyard manure and tillage systems on soil physical properties and corn yield in Central Iran. *Soil and Tillage Research*, *68*, 101–108. https://doi.org/10.1016/S0167-1987(02)00110-1

Six, J., Conant, R. T., Paul, E. A., & Paustian, K. (2002). Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, *241*, 155–176. https://doi.org/10.1023/A:1016125726789

Six, J., Elliott, E. T., & Paustian, K. (2000). Soil macroaggregate turnover and microaggregate formation: A mechanism for C sequestration under no-tillage agriculture. *Soil Biology and Biochemistry*, *32*, 2099–2103. https://doi.org/10.1016/S0038-0717(00)00179-6

Souza, E. D., Costa, S. E. V. G. A., Anghinoni, I., Carneiro, M. A. C., Martins, A. P., & Bayer, C. (2014). Soil quality indicators in a Rhodic Paleudult under long term tillage systems. *Soil and Tillage Research*, *139*, 28–36. https://doi.org/10.1016/j.still.2014.02.001

Stewart, C. E., Paustian, K., Conant, R. T., Plante, A. F., & Six, J. (2008). Soil carbon saturation: Evaluation and corroboration by long-term incubations. *Soil Biology and Biochemistry*, *40*, 1741–1750. https://doi.org/10.1016/j.soilbio.2008.02.014

Su, Y. Z., Wang, F., Suo, D. R., Zhang, Z. H., & Du, M. W. (2006). Long-term effect of fertilizer and manure application on soil-carbon sequestration and soil fertility under the wheat-wheat-maize cropping system in Northwest China. *Nutrient Cycling in Agroecosystems*, *75*, 285–295. https://doi.org/10.1007/s10705-006-9034-x

Sun, H. Y., Liu, C. M., Zhang, X. Y., Shen, Y. J., & Zhang, Y. Q. (2006). Effects of irrigation on water balance, yield and WUE of winter wheat in the North China Plain. *Agricultural Water Management*, *85*, 211–218. https://doi.org/10.1016/j.agwat.2006.04.008

Udom, B. E., & Ogunwole, J. O. (2015). Soil organic carbon, nitrogen, and phosphorus distribution in stable aggregates of an Ultisol under contrasting land use and management history. *Journal of Plant Nutrition and Soil Science*, *178*, 460–467. https://doi.org/10.1002/jpln.201400535

van Ittersum, M. K., Cassman, K. G., Grassini, P., Wolf, J., Tittonell, P., & Hochman, Z. (2013). Yield gap analysis with local to global relevance—A review. *Field Crops Research*, *143*, 4–17. https://doi.org/10.1016/j.fcr.2012.09.009

van Ittersum, M. K., & Rabbinge, R. (1997). Concepts in production ecology for analysis and quantification of agricultural input-output combinations. *Field Crops Research*, *52*, 197–208. https://doi.org/10.1016/S0378-4290(97)00037-3 van Wart, J., Grassini, P., & Cassman, K. G. (2013). Impact of derived global weather data on simulated crop yields. *Global Change Biology*, *19*, 3822–3834. https://doi.org/10.1111/gcb.12302

Wang, C., Liu, D. W., & Bai, E. (2018). Decreasing soil microbial diversity is associated with decreasing microbial biomass under nitrogen addition. *Soil Biology and Biochemistry*, *120*, 126–133. https://doi.org/10.1016/j.soilbio.2018.02.003

Wang, F. H., He, Z. H., Sayre, K., Li, S. D., Si, J. S., Feng, B., & Kong, L. G. (2009). Wheat cropping systems and technologies in China. *Field Crops Research*, *111*, 181–188. https://doi.org/10.1016/j.fcr.2008.12.004

Wang, M., Wang, L. C., Cui, Z. L., Chen, X. P., Xie, J. G., & Hou, Y. P. (2017). Closing the yield gap and achieving high N use efficiency and low apparent N losses. *Field Crops Research*, *209*, 39–46. https://doi.org/10.1016/j.fcr.2017.03.016

Xie, J., Peng, B., Wang, R., Batbayar, J., Hoogmoed, M., Yang, Y., … 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*, 555–567. https://doi.org/10.1111/ejss.12546

Yan, H. M., Cao, M. K., Liu, J. Y., & Tao, B. (2007). Potential and sustainability for carbon sequestration with improved soil management in agricultural soils of China. *Agriculture, Ecosystems & Environment*, *121*, 325–335. https://doi.org/10.1016/j.agee.2006.11.008

Yan, P., Yue, S. C., Meng, Q. F., Pan, J. X., Ye, Y. L., Chen, X. P., & Cui, Z. L. (2016). An understanding of the accumulation of biomass and nitrogen is benefit for Chinese maize production. *Agronomy Journal*, *108*, 895–904. https://doi.org/10.2134/agronj2015.0388

Yan, X. Y., & Gong, W. (2010). The role of chemical and organic fertilizers on yield, yield variability and carbon sequestration—Results of a 19-year experiment. *Plant and Soil*, *331*, 471–480. https://doi.org/10.1007/s11104-009-0268-7

Yang, Z. C., Zhao, N., Huang, F., & Lv, Y. Z. (2015). Long-term effects of different organic and inorganic fertilizer treatments on soil organic carbon sequestration and crop yields on the North China Plain. *Soil and Tillage Research*, *146*, 47–52. https://doi.org/10.1016/j.still.2014.06.011

Ye, Y. L., Wang, G. L., Huang, Y. F., Zhu, Y. J., Meng, Q. F., Chen, X. P., … Cui, Z. L. (2011). Understanding physiological processes associated with yield-trait relationships in modern wheat varieties. *Field Crops Research*, *124*, 316–322. https://doi.org/10.1016/j.fcr.2011.06.023

Yin, Y. L., Ying, H., Xue, Y. F., Zheng, H. F., Zhang, Q. S., & Cui, Z. L. (2019). Calculating socially optimal nitrogen (N) fertilization rates for sustainable N management in China. *Science of the Total Environment*, *688*, 1162–1171. https://doi.org/10.1016/j.scitotenv.2019.06.398

Zhang, F. S., Cui, Z. L., Fan, M. S., Zhang, W. F., Chen, X. P., & Jiang, R. F. (2011). Integrated soil-crop system management: Reducing environmental risk while increasing crop productivity and improving nutrient use efficiency in China. *Journal of Environmental Quality*, *40*, 1051–1057. https://doi.org/10.2134/jeq2010.0292

Zhang, H. B., Luo, Y. M., Wu, L. H., Huang, Y. J., & Christie, P. (2015). Residues and potential ecological risks of veterinary antibiotics in manures and composts associated with protected vegetable farming. *Environmental Science and Pollution Research*, *22*, 5908–5918. https://doi.org/10.1007/s11356-014-3731-9

Zhang, H. P., Turner, N. C., & Poole, M. L. (2012). Increasing the harvest index of wheat in the high rainfall zones of southern Australia. *Field Crops Research*, *129*, 111–123. https://doi.org/10.1016/j.fcr.2012.02.002

Zhang, W. J., Wang, X. J., Xu, M. G., Huang, S. M., Liu, H., & Peng, C. (2010). Soil organic carbon dynamics under long-term fertilizations in arable land of northern China. *Biogeosciences*, *7*, 409–425. https://doi.org/10.5194/bg-7-409-2010

Zheng, X. H., Han, S. H., Huang, Y., Wang, Y. S., & Wang, M. X. (2004). Requantifying the emission factors based on field measurements and estimating the direct $N_2O$ emission from Chinese croplands. *Global Biogeochemical Cycles*, *18*, GB2018. https://doi.org/10.1029/2003GB002167

Zhu, P., Ren, J., Wang, L. C., Zhang, X. P., Yang, X. M., & MacTavish, D. (2007). Long-term fertilization impacts on corn yields and soil organic matter on a clay-loam soil in Northeast China. *Journal of Plant Nutrition and Soil Science*, *170*, 219–223. https://doi.org/10.1002/jpln.200620635

Zhuang, J., McCarthy, J. F., Perfect, E., Mayer, L. M., & Jastrow, J. D. (2008). Soil water hysteresis in water-stable microaggregates as affected by organic matter. *Soil Science Society of America*, *72*, 212–220. https://doi.org/10.2136/sssaj2007.0001S6

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

**How to cite this article:** Guo Y, Chen M, Pan J, Shang Y, Wu X, Cui Z. Increasing soil organic carbon sequestration while closing the yield gap in Chinese wheat production. *Land Degrad Dev*. 2021;32:1274–1286. https://doi.org/10.1002/ldr.3747