

# Crop Yield Response to Soil Organic Carbon Stock over Long-Term Fertilizer Management in Huang-Huai-Hai Plains of China

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**Abstract** Huang-Huai-Hai (HHH) plains of China account for 69.2 % of annual wheat (*Triticum aestivum*) and 35.3 % of annual maize (*Zea mays*) production in China, and are China's principal crop production area. Thus, the understanding of crop yield response to increase in soil organic carbon (SOC) stock in different fertilizer managements, soil types, and the threshold of SOC stock in the HHH region is the key factor affecting the adoption of fertilizer managements. Thus, data from ten long-term experiments have been collated and synthesized in this article. These long-term experiments involved four groups of similar fertilizer managements: (i) no chemical fertilizer or organic as control (CK), (ii) chemical nitrogen (N) fertilizer applied without organic manure (UF), (iii) combined application of chemical fertilizer (N, P, K) without organic manure (CF), and (iv) integrated nutrient management (INM) based on use of manure/straw and chemical fertilizer (N, P, K). The results indicated that (i) Crop yield increased with increase in SOC stock in all sites across the HHH. Increase in SOC stock by one Mg ha<sup>-1</sup> increased crop yield (kg ha<sup>-1</sup> year<sup>-1</sup>) from 66.9 in Changpin to 333.2 in XinjiA and 495.2 in XinjiB in sub-region 1, 1,031.4 in HengshuiA, 419.2 in HengshuiB, and 148.5 in Yucheng in sub-region 2, and 914.2 in ZhengzhouA, 1,116.6 in ZhengzhouB, 1,135.6 in Xuzhou, and 437.3 in Mengcheng in sub-region 3. (ii) The magnitude of increase in crop yield with increase in SOC stock varied among CK,UF,CF, and INM treatments for different sites across the HHH. A gradual but sustainable increase was observed through SOC-induced improvements in soil quality. (iii) The threshold value of SOC stock for sub-region 1 was 44.9 Mg ha<sup>-1</sup> in XinjiA with the corresponding crop yield of 12.3 Mg ha<sup>-1</sup> year<sup>-1</sup>. The available data were not sufficient to identify the threshold level of SOC stock for sub-region 2. The threshold values of SOC stock(Mg ha<sup>-1</sup>) for sub-region 3 were 27.5 in Xuzhou, and 44.6 in Mengcheng with the corresponding crop yield(Mg ha<sup>-1</sup> year<sup>-1</sup>) of 14.5 and 10.5, respectively. (v)The threshold value of SOC stock in response to crop yield for the entire HHH ranged from 25.0 to 41.0 Mg ha<sup>-1</sup>, and the corresponding potential of increase in crop yield from 12.8 to 18.0 Mg ha<sup>-1</sup> year<sup>-1</sup>. In comparison with a rapid yield response by application of chemical fertilizers, increase in SOC stock and improvement in soil quality result in a gradual but sustainable yield increase. Thus, restoration of the depleted SOC stock by conversion to a restorative land use and adoption of INM across the HHH can enhance soil quality and improve crop production.

**Keywords** Crop yields · Soil organic carbon · Huang-Huai-Hai plains · Soil quality

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## Abbreviations

SOC: Soil organic carbon; HHH: Huang-Huai-Hai plains; C: Carbon; GHG: Greenhouse gas; CK: Control treatment; N: Chemical nitrogen; UF: Chemical nitrogen (N) fertilizer applied without organic manure; CF: Combined application of chemical fertilizer (N, P, K) without organic manure; INM: Integrated nutrient management based on use of manure/straw and chemical fertilizer (N, P, K);

## Introduction

The multi-pronged challenges faced by developing countries with regard to food insecurity include limited availability of high quality arable land and the necessity to increase crop yields. The Green Revolution technology, growing input-responsive varieties on favorable soils, progressively increased global average grain yields of cereals ( $\text{Mg ha}^{-1}$ ) to 1.8 in 1970, 2.2 in 1980, 2.8 in 1990, and 3.1 in 2000, respectively [4]. However, it is becoming difficult to increase crop yields because of low soil organic carbon (SOC) stock because of the accelerated erosion, negative soil carbon (C) budget, and climatic change [18]. However, the required increase in crop production in developing countries (i.e., China, India) will have to be achieved, despite the degrading soils [13]. Thus, the strategy is to increase crop production without increasing either the land area or the chemical fertilizer used. Therefore, increase in SOC stock by sustainable practices of soil fertility and fertilizers management is an important choice for the developing countries to improve crop production.

There exists a strong relationship between crop production and the SOC stock, especially in low-input agriculture (none or low rate of fertilizer input) [13]. The beneficial effects of increase in SOC stock on crop yields have been widely reported [6, 11]. Increasing the SOC stock of degraded cropland soils in the root zone can enhance crop production ( $\text{kg grains ha}^{-1} \text{ Mg C}^{-1}$ ) at the rate of 20–40 for wheat (*Triticum aestivum*), 200–300 for maize (*Zea mays*), and 30–60 for cowpeas (*Vigna unguiculata*) [13]. The data from Australia indicated a decline in yield of wheat with depletion, increase in yield with accretion, and a stable yield of  $\sim 2.75 \text{ Mg ha}^{-1}$  with a steady-state level of the SOC stock [5]. Thus, an optimal level of the SOC stock is an essential determinant of high and sustainable crop yield. However, there is no research specifically conducted to quantify the impacts of increase in SOC stock on crop yield in the Huang-Huai-Hai plains (HHH) of China.

The HHH region comprises about 16 % of the China's arable land [10], and it plays an important role in sustaining food security and mitigating greenhouse gas (GHG) emissions [21]. The HHH is the primary wheat–maize growing area. Since 1980s, it accounts for 69.2 % of annual wheat and 35.3 % of annual maize production [17],

and is China's principal crop production region [9, 10]. Most of the past research has focused on in situ beneficial impacts of residue retention [30], chemical fertilizers [3], and use of organics for enhancing SOC stock and increasing crop yield [8]. In addition to organics, use of balanced fertilizers can also enhance SOC stock and improve crop yield [28]. Experiments conducted in other regions of China have also indicated a possible impact of increase in SOC stock on improvement in crop yield [19, 29]. The minimum threshold value of  $7.54 \text{ g kg}^{-1}$  of SOC stock has been reported to achieve the crop yield of  $15.0 \text{ Mg ha}^{-1}$  in the HHH [27]. The empirical relationships between soil organic matter (SOM) and crop yield in different ecosystems at national level indicate that for every 1 % increase in SOM, the corresponding increase in total cereal productivity is  $0.43 \text{ Mg ha}^{-1} \text{ year}^{-1}$  along with a decrease of yield variability against disturbance by 3.5 % [20]. Thus, quantifying the impact of increase in SOC stock on crop yield is necessary to adopt strategies of improving soil quality and advancing crop yields [12, 22].

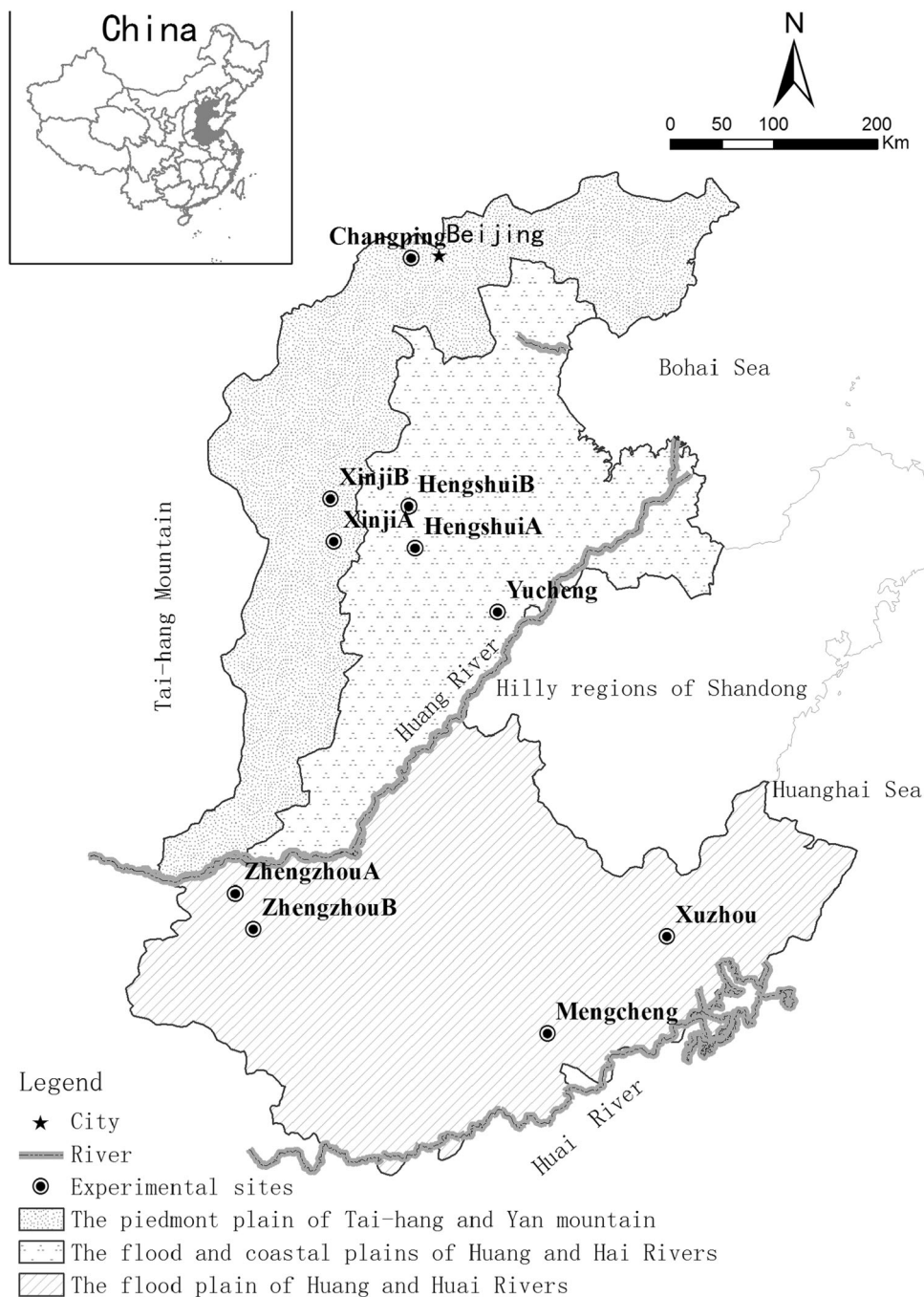
While the beneficial effects of different fertilizer management treatments on soil quality and crop yields at specific experiments in different soil types have been reported in the HHH, there is a lack of relevant data quantifying the uniform and individual trends regarding the effects of increase in SOC stock on crop yields for different fertilizer managements, and soil types across the entire HHH at macro-level. Therefore, the objective of this research was to (i) quantify the individual trends of effects of increase in SOC stock on crop yields for different fertilizer managements under different soil types, and determine the uniform trends of effects of increase in SOC stock on crop yield over time across the HHH region, and (ii) quantify the diversity trends in threshold of SOC stock and potential of increase in crop yield among different soil subgroups by improvement in the SOC stock.

## Materials and Methods

### Experimental Sites and Soil Types

The HHH plains, located in northern China, are formed by alluvial sediments deposited by three rivers (i.e., the Huang River or Yellow River, Huai River, and Hai River) (Fig. 1). It is the largest plain and constitutes an important

**Fig. 1** Sites of ten long-term experiments



agricultural region in China. It covers a total area of 320,000 km<sup>2</sup>, with 18.67 million ha (M ha) of arable land and a population of 200 million [17]. The annual rainfall ranges from 461.9 to 837.3 mm, the annual cumulative temperature from 4,874.0 to 5,368.2 degree days, and the annual average temperature from 12.8 to 14.6 °C (Table 1). The region is characterized by an intensive use of irrigation and chemical fertilizers, and the predominant cropping system is double-cropping of winter wheat and summer maize.

The entire HHH is divided into three sub-regions, on the basis of soil, water distribution, temperature, precipitation, and agricultural management [23] (Fig. 1). Sub-region 1 comprises the piedmont plain of Tai-hang and Yan mountains. Principal soils of the sub-region include argillic fluvo-udic and fluvo-aquic *Inceptisols*. The groundwater table is deep, and salt concentration is low (<0.1 % in soil profile). Sub-region 2 comprises the flood and coastal plains of Huang and Hai rivers. Principal soil types are light, medium, and heavy saline fluvo-aquic *Inceptisols*. The sub-

**Table 1** Soil and Climate environments of ten long-term experiments across the Huang-Huai-Hai plains

Sites	Location		Annual rainfall mm year <sup>-1</sup>	Annual accumulative temperature >0 °C	Annual average temperature °C	Experiment duration year	Soil properties		Soil subgroup in China	USA	
	Province	Latitude					Longitude	pH			Soil texture
Chang pin	Beijing	40°10'	574.1	4,874.0	12.8	1991–2005	8.8	Clay loam	1.3	Mottli-argic endorustic Udic Cambosols	Inceptisols
Xinji A	Hebei	37°54'	461.9	5,015.7	13.2	1979–1999	8.3	Silt loam	1.4	Calic-endorusti Aquic Cambosols	Inceptisols
Xinji B	Hebei	37°55'	461.9	5,015.7	13.2	1979–1999	8.2	Silt loam	1.4	Mottli-endorusti Aquic Cambosols	Inceptisols
Hengshui A	Hebei	37°42'	478.1	4,996.3	13.2	1979–2002	8.3	Loam	1.4	Mottli-endorustic Aquic Cambosols	Inceptisols
Hengshui B	Hebei	37°43'	478.1	4,996.3	13.2	1979–2002	8.2	Loam	1.5	Mottli-argic Aquic Cambosols	Inceptisols
Yucheng	Shandong	36°50'	582.0	4,951.0	13.4	1987–2005	8.3	Loam	1.3	Mottli-Salic Aquic Cambosols	Inceptisols
Zhengzhou A	Henan	34°46'	623.2	5,334.0	14.4	1980–2000	8.1	Loam	1.5	Mottli-endorustic Aquic Cambosols	Inceptisols
Zhengzhou B	Henan	34°47'	623.2	5,334.0	14.4	1990–1999	8.3	Loam	1.5	Mottli-argic Aquic Cambosols	Inceptisols
Xuzhou	Jiangsu	33°54'	837.3	5,368.2	14.6	1980–2005	8.3	Sand loam	1.4	Xanthic-enorustic Aquic Cambosols	Inceptisols
Mengcheng	Anhui	33°52'	790.1	5,436.8	14.7	1994–2001	6.3	Clay	1.6	Shajiang-Claypannic Aquic Cambosols	Inceptisols

region has saline phreatic water reserves (2–10 g L<sup>-1</sup>) [23], which may exacerbate the risks of salinization. Sub-region 3 comprises the flood plains of Huang and Huai rivers. Principal soil types are yellow fluvo-aquic and light saline fluvo-aquic *Inceptisols*, and relatively high rainfall leaches salts into the sub-soil.

### Experiment Design and Managements

Prior to 1980s, crop yields were low across the entire HHH region. Thus, a project on the sustainable and comprehensive management was initiated to develop technologies for improving crop productivity [23]. To begin with, crop yields were increased by reclamation of salt-affected soils [2]. Therefore, a series of long-term experiments were established from 1979 to 1991 at different soil types to assess the effects of fertilizer management on crop yield and SOM concentration (Table 1). The typical soil types in the HHH region are Udior Aquic Cambosols according to the Chinese Soil Taxonomy system.

Crop yield and SOC data were collated and synthesized from ten long-term experiments conducted between 1980 and 2005 across the HHH (Table 1). Ten sites are divided into three sub-regions: (i) 3 sites in sub-region 1 (1 site in Beijing and 2 in Hebei province); (ii) 3 sites in sub-region 2 (2 sites in Hebei and 1 in Shandong province); and (iii) 4 sites in sub-region 3 (2 sites in Henan, 1 each in Jiangsu and Anhui province). However, the duration of the ten long-term experiments is not the same. For example, the duration of experiment ranged from 1980 to 2000 in Zhengzhou A, 1994 to 2001 in Mengcheng, 1979 to 2002 in Henshui A, respectively. Yet, the data provide us scientific basis for evaluation of the general effects of the increase in SOC stock under different fertilizer managements across the HHH region, the uniform trend of effects of increase in SOC stock on crop yield, and the threshold value of SOC stock.

Experimental duration varied from 1 to 3 for every treatment across the long-term experiments, and the plot area varied from 40 to 100 m<sup>2</sup> [16]. The ten long-term experiments had different fertilizer management treatments, and the rate of application of chemical fertilizer N, P, K, and organic manure in these treatments (Table 2) was designed, according to the local household fertilizer managements and the soil nutrients across the different soil types in HHH.

For the purpose of macro-level study, all treatments in different agro-ecosystems across the HHH region are grouped into a total of 4 fertilizer managements (Table 2) as follows: (i) no chemical fertilizer or organic manure as control treatment (CK); (ii) chemical nitrogen(N) fertilizers applied without organic manure (UF); (iii) combined application of chemical fertilizer (N, P, K) without organic

manure (CF); and (iv) integrated nutrients management (INM) involving application of manure/straw along with chemical fertilizers (N, P, K).

With an exception of the four fertilizer managements, all other farm operations and managements were similar at all long-term experiments. Winter wheat was sown in October and harvested in early June of the next year. Summer maize was sown in June and harvested in October. Winter wheat was irrigated 2–3 times and maize 1–2 times [16] depending on the precipitation amount and distribution during the season. The volume of water used for each irrigation was 900 (9 cm) to 12 00 (12 cm) m<sup>3</sup> ha<sup>-1</sup>. Herbicides and pesticides were applied to control weeds and reduce insect pressure, respectively. Organic and chemical fertilizers including P and K were applied as basal dose, but 1/3 to 2/3 of N was applied as basal dose and remaining was top-dressed for wheat. However, all the fertilizers were top-dressed in maize [15].

#### Soil Organic Carbon and Crop Yield Data Base

Soil samples for assessing the SOC concentration were obtained from 0 to 20 cm depth for all sites after harvest of maize every year between 1980 and 2005. These soil samples were selected to analyze SOC concentration by the wet combustion method (Tiessen, 1993), bulk density by the core method [25], and texture by the hydrometer method [7]. Soil texture ranged from silt clay loam, loam, silt loam to loam [25]. Grain and residues yields were recorded for each growing season. Wheat and maize were harvested at the soil surface level, thus stubble left in the field was negligible, but roots were left in the soil. All straws were removed from the field. Grain and straw were weighed separately after air drying [16].

The data for treatments including CK, UF, CF, and INM were obtained for the period from 1991 to 2005 in Changpin, 1979 to 1999 in Xinji A and B, from in Zhengzhou A and B, from 1980 to 2005 in Xuzhou, respectively. The data for treatments including CK, CF, and INM ranged from 1979 to 2002 in Hengshui A, 1987 to

2005 in Yucheng, respectively. The data for treatments CK and CF ranged from 1979 to 2002 in Hengshui B. The data for CK and UF ranged from 1994 to 2001 in Mengcheng (Table 3). The data on SOC concentration were normalized and converted to SOC stock [15] using equation as follows:

$$\text{SOC stock (Mg ha}^{-1}\text{)} = \text{SOM (g kg}^{-1}\text{)} * 10^4 \text{ m}^2 \text{ha}^{-1} * 0.2 \text{m} * \text{SBD (Mg m}^{-3}\text{)} * 10^{-3}$$

where SOC concentration is in g kg<sup>-1</sup> at 20 cm depth, and soil bulk density (SBD) is in Mg m<sup>-3</sup>.

#### Data Processing and Statistics

Data were organized into SOC stock and crop yield for CK, UF, CF, and INM treatments for different sites. The data of trend lines of crop yield response to increase in SOC stock for different experimental sites were computed using Microsoft Excel 2007. Significance of differences at  $P < 0.05$  and  $P < 0.01$  between fertilizer managements in different long-term experimental sites was tested using SPSS (Version 13.0).

## Results

### Crop yield Response to SOC Stock at the Similar Fertilizer Managements in Different Soil Types

Response of crop yield to SOC stock for different fertilizer treatments in 10 long-term experimental sites is shown in Table 3.

#### (a) CK treatment:

Response of crop yield to SOC stock for CK treatments in 10 long-term experimental sites is shown in Table 3, and trends differed among sub-regions. Increase in SOC stock resulted in the following yield response among different sub-regions: (i) yield decreased at 2 and increased at 1

**Table 2** Application of chemical fertilizer and organic manures under different treatments

Treatments	C (kg hm <sup>-2</sup> )	N (kg hm <sup>-2</sup> )	P <sub>2</sub> O <sub>5</sub> (kg hm <sup>-2</sup> )	K <sub>2</sub> O (kg hm <sup>-2</sup> )
CK	0	0	0	0
UF	0	135–360	0	0
CF	0	135–360	60–150	60–150
INM	500–6,000	147–480	72–320	90–350

The application amount of fertilization under different treatment was calculated and synthesized based on ten designs in eight experimental sites. CK no use of either chemical fertilizers or organic manure as control treatment, CF combined application of chemical fertilizer N, P, and K without organic manure, UF chemical nitrogen (N) fertilizers applied separately and without organic manure, INM integrated nutrient management based on manure/straw and application of chemical fertilizer N, P, and K and organic fertilizers.

**Table 3** Crop yield response to SOC stock at the similar fertilizer managements in different soil types

Managements	Region	Sites	Trend line model	$R^2$
CK	Subregion1	Changpin	$y = -133.52x + 5,405.8$	$R^2 = 0.24$
		XinjiA	$y = 101.61x + 3,792.2$	$R^2 = 0.02$
		XinjiB	$y = -550.29x + 15,449$	$R^2 = 0.13$
	Subregion3	ZhengzhouA	$y = -109.46x + 6,842.7$	$R^2 = 0.01$
		ZhengzhouB	$y = 660.9x - 7,122.1$	$R^2 = 0.42$
		Xuzhou	$y = 156.75x + 3,093$	$R^2 = 0.06$
		Mengcheng	$y = -539.56x + 14,850$	$R^2 = 0.05$
	Subregion2	Yucheng	$y = -72.701x + 5,200.5$	$R^2 = 0.29$
		HengshuiA	$y = 577x - 6,924.5$	$R^2 = 0.44$
		HengshuiB	$y = -72.701x + 5,200.5$	$R^2 = 0.01$
UF	Subregion1	Changpin	$y = -179.66x + 6,991.3$	$R^2 = 0.12$
		XinjiA	$y = 49.92x + 5,025.6$	$R^2 = 0.01$
		XinjiB	$y = 151.2x + 2,862.1$	$R^2 = 0.01$
	Subregion3	ZhengzhouA	$y = 782.18x - 8,439$	$R^2 = 0.06$
		ZhengzhouB	$y = -783.54x + 21,795$	$R^2 = 0.06$
		Xuzhou	$y = 610.47x - 631.1$	$R^2 = 0.05$
		Mengcheng	$y = 118.29x + 8,618$	$R^2 = 0.05$
CF	Subregion1	Changpin	$y = -313.07x + 15,250$	$R^2 = 0.11$
		XinjiA	$y = 394.68x + 1,215.4$	$R^2 = 0.17$
		XinjiB	$y = 797.17x - 6,258.8$	$R^2 = 0.28$
	Subregion3	ZhengzhouA	$y = 273.89x + 5,263.8$	$R^2 = 0.03$
		ZhengzhouB	$y = 394.46x + 4,212.4$	$R^2 = 0.14$
		Xuzhou	$y = 402.92x + 6,409.2$	$R^2 = 0.05$
	Subregion2	Yucheng	$y = -121.32x + 14,556$	$R^2 = 0.02$
		HengshuiA	$y = 725.72x - 5,950.6$	$R^2 = 0.06$
		HengshuiB	$y = -47.39x + 8,017.4$	$R^2 = 0.01$
INM	Subregion1	Changpin	$y = 69.74x + 7,748.2$	$R^2 = 0.01$
		XinjiA	$y = 62.34x + 8,164.6$	$R^2 = 0.32$
		XinjiB	$y = 638.53x - 4,339.3$	$R^2 = 0.23$
	Subregion3	ZhengzhouA	$y = -389.6x + 21,780$	$R^2 = 0.06$
		ZhengzhouB	$y = -30.06x + 13,386$	$R^2 = 0.01$
		Xuzhou	$y = -107.97x + 17,586$	$R^2 = 0.19$
	Subregion2	Yucheng	$y = 7.03x + 13,339$	$R^2 = 0.0,002$
		HengshuiA	$y = 878.82x - 11,240$	$R^2 = 0.35$

$y$  is the yield and  $x$  is the corresponding SOC stock for the same fertilizer managements

site in sub-region 1, (ii) decreased at 2 and increased at 1 site in sub-region 2, and (iii) decreased at 2 and increased at 2 sites in sub-region 3. In sites where there was an increasing trend, increase in SOC stock by 1 Mg ha<sup>-1</sup> increased crop yield (kg ha<sup>-1</sup> year<sup>-1</sup>) by 101.6 in sub-region 1, 577.0 in sub-region 2, and 660.9 in sub-region 3. In contrast, the sites where the decreasing trend was observed, the rate of decrease (kg ha<sup>-1</sup> year<sup>-1</sup>) with increase in SOC stock ranged from -550.3 to -133.5 in sub-region 1, -72.7 to -1147.2 in sub-region 2, -109.5 to -539.6 in sub-region 3.

(b) *UF treatment:*

Crop yield responses to SOC stock for UF treatments show that increase in SOC stock by 1 Mg ha<sup>-1</sup> affected crop response as follows: (i) yield increased at 2 and decreased at 1 site in sub-region 1, (ii) increased at 1 and decreased at 1 site in sub-region 2, and (iii) increased at 2 sites in sub-region 3. The rate of increase in crop yield (kg ha<sup>-1</sup> year<sup>-1</sup>) for every 1 Mg ha<sup>-1</sup> increase in SOC stock ranged from 49.9 to 151.2 in sub-region 1, 782.2 in sub-region 2, and 118.3 to 610.5 in sub-region 3. In contrast, the rate of

decrease in crop yield ( $\text{kg ha}^{-1} \text{ year}^{-1}$ ) across the HHH for every  $1 \text{ Mg ha}^{-1}$  increase in SOC stock was  $-179.7$  in sub-region 1, and  $-783.5$  in sub-region 2.

(c) *CF treatment:*

Crop yield responses to SOC stock for CF treatments show that increase in SOC stock by  $1 \text{ Mg ha}^{-1}$  affected crop response as follows: (i) yield increased at 2 and decreased at 1 site in sub-region 1, (ii) increased at 1 and decreased at 2 sites in sub-region 2, and (iii) increased at all sites in sub-region 3. The rate of increase in crop yield ( $\text{kg ha}^{-1} \text{ year}^{-1}$ ) for every  $1 \text{ Mg ha}^{-1}$  increase in SOC stock increased from 394.7 in sub-region 1, 725.7 in sub-region 2, and from 273.9 to 402.9 in sub-region 3. In contrast, the rate of decrease in crop yield ( $\text{kg ha}^{-1} \text{ year}^{-1}$ ) for every  $1 \text{ Mg ha}^{-1}$  increase in SOC stock was  $-313.1$  in sub-region 1, from  $-47.4$  to  $-121.3$  in sub-region 2.

(d) *INM treatment:*

Crop yield responses to SOC stock under INM treatments show that increase in SOC stock by  $1 \text{ Mg ha}^{-1}$  affected crop response as follows: (i) yield increased at all sites in sub-region 1 and sub-region 2, and (ii) decreased at all sites in sub-region 3. The rate of increase in crop yield ( $\text{kg ha}^{-1} \text{ year}^{-1}$ ) for every  $1 \text{ Mg ha}^{-1}$  increase in SOC stock ranged from 62.3 to 638.5 in sub-region 1, and 7.0 to 878.0 in sub-region 2. In contrast, the rate of decrease in crop yield ( $\text{kg ha}^{-1} \text{ year}^{-1}$ ) for every  $1 \text{ Mg ha}^{-1}$  increase in SOC stock was  $-30.1$  to  $-389.6$  in sub-region 3.

The data indicate diverse patterns of crop yield response to change in SOC stock among CK, UF, CF, and INM treatments. The results presented indicate that yield response to SOC stock also varied with fertilizer managements among soil subgroups, experiment duration, and agro-ecosystem. Within the same experimental site, crop yield increased with increase in SOC stock for some fertilizer treatments, but decreased for others.

#### Crop Yield Response to SOC Stock in Different Soil Types

In contrast to diverse trends of crop yield response to SOC stock for different fertilizer treatments, the effects of increase in SOC stock on crop yields for different soil subgroups across the HHH show similar increasing trends. These increasing trends were observed whenever the antecedent SOC stock was below the threshold level.

Increase in SOC stock by  $1 \text{ Mg ha}^{-1}$  in sub-region 1 increased crop yield ( $\text{kg ha}^{-1} \text{ year}^{-1}$ ) from 66.9 in Changpin to 333.2 in XinjiA and 495.2 in XinjiB. The magnitude of increase in crop yield ( $\text{kg ha}^{-1} \text{ year}^{-1}$ ) in

sub-region 2 for every  $1 \text{ Mg ha}^{-1}$  increase in SOC stock was 1,031.4 in HengshuiA, 419.2 in HengshuiB, and 148.5 in Yucheng. In sub-region 3, increase in crop yield ( $\text{kg ha}^{-1} \text{ year}^{-1}$ ) with increase in SOC stock by one  $\text{Mg ha}^{-1}$  was 914.2 in ZhengzhouA, 1,116.6 in ZhengzhouB, 1,135.6 in Xuzhou, and 437.3 in Mengcheng.

The threshold values of SOC stock also varied among sub-regions. The threshold value ( $\text{Mg ha}^{-1}$ ) was 44.9 in sub-region 1, 44.6 in sub-region 3, and no threshold value of SOC stock was observed in sub-region 2. Crop yield was stable beyond the threshold value of SOC stock in sub-regions 1 and 2.

Crop yield responses to SOC stock for ten different soil types in Fig. 2 show (i) increasing trends for experiments conducted for long duration, (ii) increasing crop yield with increase in SOC stock in all soil types across the HHH, and (iii) occurrence of the threshold values of SOC stock only for sub-region 1 and sub-region 3.

#### Potential of Increasing Crop Yield in Different Soil Types

Regression equations relating response of crop yield to increase in SOC stock for different sites across the region are shown in Fig. 2. The threshold and the maximum values of SOC stock, and the corresponding potential crop yields are shown in Table 4.

(a) Sub-region 1:

The threshold value of SOC stock in sub-region 1 was  $44.9 \text{ Mg ha}^{-1}$  in XinjiA and the corresponding crop yield of  $12.3 \text{ Mg ha}^{-1} \text{ year}^{-1}$ , and the maximum SOC stock of 28.9 and  $25.4 \text{ Mg ha}^{-1}$  for two sites with corresponding crop yield of 6.2 and  $10.6 \text{ Mg ha}^{-1} \text{ year}^{-1}$ , respectively. The SOC stock in these 2 sites was presumably below the threshold level.

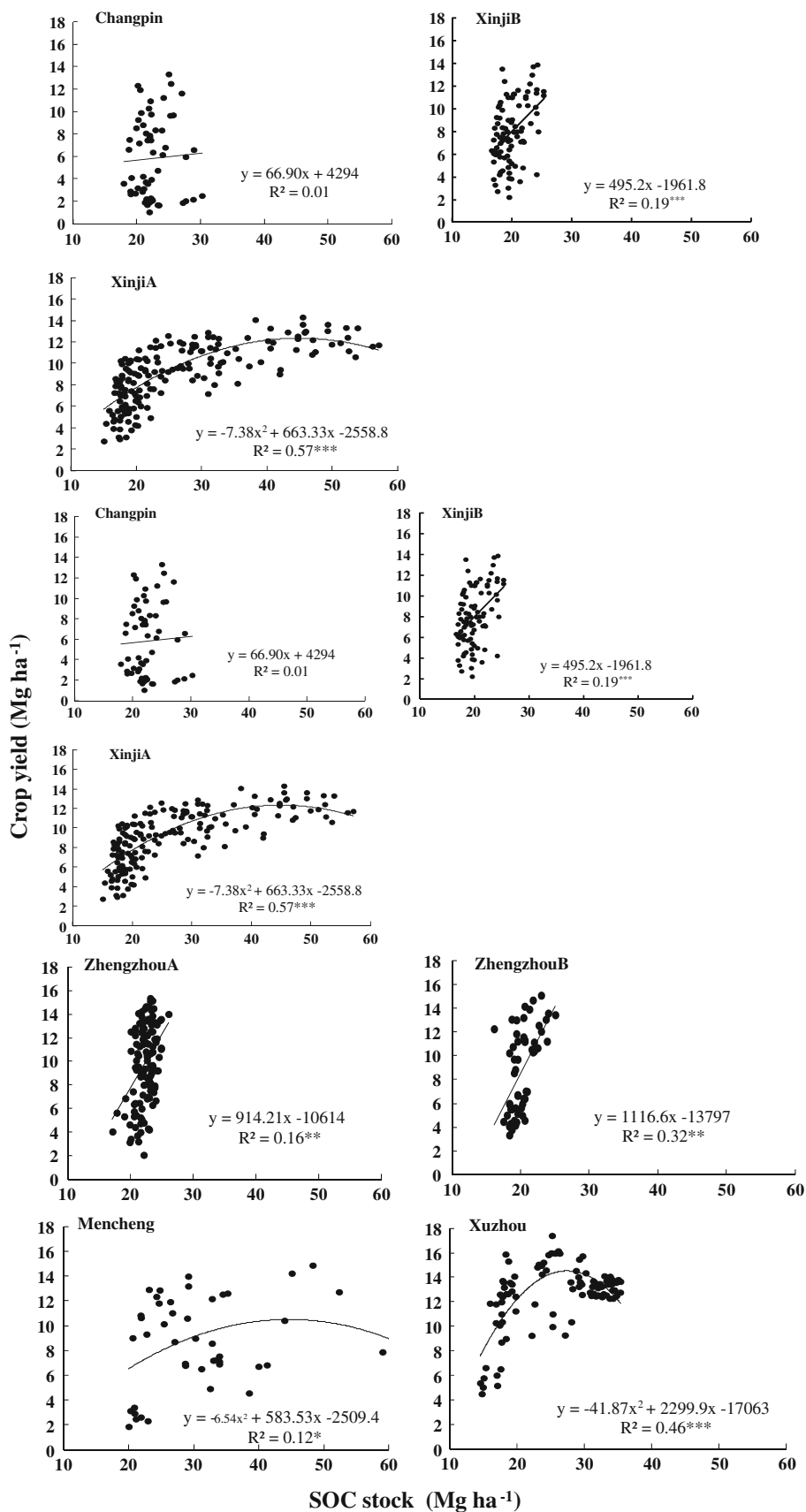
(b) Sub-region 2:

The data were not of an adequate range to identify the threshold level of the SOC stock in sub-region 2. However, the maximum value can be calculated using regression equations. The maximum values of SOC stock were  $34.7 \text{ Mg ha}^{-1}$  in Yucheng,  $26.7 \text{ Mg ha}^{-1}$  in HengshuiA, and  $26.2 \text{ Mg ha}^{-1}$  in HengshuiB with the corresponding crop yields ( $\text{Mg ha}^{-1} \text{ year}^{-1}$ ) of 14.3, 13.6, and 8.5, respectively.

(c) Sub-region 3:

For four sites in sub-region 3, threshold values of SOC stock ( $\text{Mg ha}^{-1}$ ) were 27.5 in Xuzhou, and 44.6 in Mengcheng with the corresponding crop yield ( $\text{Mg ha}^{-1} \text{ year}^{-1}$ ) of 14.5 and 10.5, respectively. The maximum values of SOC stock ( $\text{Mg ha}^{-1}$ ) were 26.1 in ZhengzhouA,

**Fig. 2** Crop yield response to changes in soil organic carbon stock in 10 long-term experiments





**Table 4** Regression equation and the threshold and maximum value of soil organic carbon stock and the corresponding estimated crop yield

Region	Sites	Trend line model	$R^2$	Yield(kg ha <sup>-1</sup> )		SOC(Mg ha <sup>-1</sup> )	
				Threshold	Maximum	Threshold	Maximum
Subregion1	Changpin	$y = 66.9x + 4,294$	$R^2 = 0.01$		6,229.4		28.93
	XinjiA	$y = -7.38x^2 + 663.33x - 2,558.8$	$R^2 = 0.57^{***}$	12,346.6		44.9	
	XinjiB	$y = 495.2x - 1,961.8$	$R^2 = 0.16^{***}$		10,617.6		25.4
Subregion3	ZhengzhouA	$y = 914.21x - 10,614$	$R^2 = 0.16^{***}$		13,246.9		26.1
	ZhengzhouB	$y = 1,116.6x - 13,797$	$R^2 = 0.32^{***}$		14,229.7		25.1
	Xuzhou	$y = -41.87x^2 + 2,299.9x - 17,063$	$R^2 = 0.46^{***}$	14,520.11		27.5	
	Mengcheng	$y = -6.54x^2 + 583.53x - 2,509.4$	$R^2 = 0.12^*$	10,506.9		44.6	
Subregion2	Yucheng	$y = 148.5x + 9,116.1$	$R^2 = 0.10^*$		14,261.6		34.7
	HengshuiA	$y = 1,031.4x - 13,924$	$R^2 = 0.39^{***}$		13,614.4		26.7
	HengshuiB	$y = 419.18x - 2,446.3$	$R^2 = 0.21^{***}$		8,536.2		26.2
HHH region		$y = -12.96x^2 + 1,061.6x - 8,925.1$	$R^2 = 0.24^{**}$	12,814.7		41.0	

\*, \*\* and \*\*\* indicate the significance of the soil organic carbon(SOC) stock trends at  $P < 0.05$ ,  $< 0.01$ , and  $< 0.001$

$y$  is the yield and  $x$  is the corresponding SOC stock in the same site

and 25.1 in ZhengzhouB with the corresponding maximum crop yield (Mg ha<sup>-1</sup> year<sup>-1</sup>) of 13.2 and 14.2, respectively.

Pooling all the SOC stocks and the corresponding crop yield data under different fertilizer managements in 10 experimental sites in Fig. 3 indicates that the response of crop yield to SOC stock can be divided into two groups. In the first group, the SOC stock ranged from 15.0 to 25.0 Mg ha<sup>-1</sup> and the corresponding crop yield from 2.0 to 18.0 Mg ha<sup>-1</sup> year<sup>-1</sup>. In the second group, the SOC stock ranged from 25.0 to 41.0 Mg ha<sup>-1</sup> and the corresponding crop yield from 12.8 to 18.0 Mg ha<sup>-1</sup> year<sup>-1</sup>.

Thus, for the HHH plains as a whole, the threshold value of SOC stock was 25.0 to 41.0 Mg ha<sup>-1</sup> for high crop yield. While the increase in crop yield is strongly impacted by increase in SOC stock in different soil types across the region, the threshold value of SOC stock for increase in crop yield was observed only in 3 sites among 10 different soil subgroups. Because of large differences in annual cumulative temperature, average annual temperature, and precipitation from north to south, the site-specific response of crop yield to SOC stock differs across the HHH. Nonetheless, crop response is strong for SOC stock between 25.0 and 41.0 Mg ha<sup>-1</sup>.

## Discussion

### Crop Yield Response to SOC Stock in Specific Fertilizer Managements

The results for specific fertilizer managements in long-term experimental sites across the HHH are not in accord with those reported by [Benbi and Chand [1]] from India. These trends indicate that factors affecting yield response to SOC

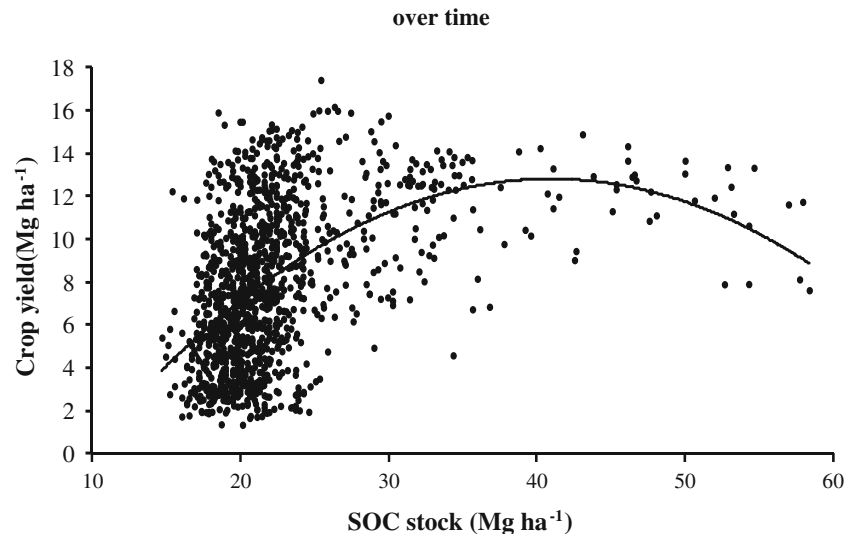
stock depend not only on fertilizer managements but also on weather conditions and other site-specific factors during growing season (Smith, 2,011). Furthermore, factors affecting SOC stock and crop yield under specific fertilizer managements not only depend on the rate of fertilizer but also on soil quality and duration of fertilizer application [30], 3]. The SOC stock under specific fertilizer managements is relatively stable, but crop yields exhibit large variations because of numerous exogenous factors. Thus, yield responses to increase in SOC stock differ among fertilizer managements and soil types across the HHH.

The crop yield did not respond to increase in SOC stock at specific fertilizer management level under long-term experiments. On the contrary, the yield increased with increase in SOC stock at all soils across the HHH. Such a trend indicates that the crop yield increased with increase in SOC stock whenever there was conversion from either none or unbalanced fertilizer management to INM. The increase in crop yield by increase in SOC stock is a gradual process and occurs over a long time of decades. These results support the hypothesis that crop production in developing countries can be increased by improving soil quality through increase in SOC stock by adoption of recommended management practices (RMPs) [12]. Thus, it will need long time to restore the depleted SOC stock by conversion to a restorative land use and adoption of RMPs across the HHH.

The threshold value of the increase in SOC stock in the HHH region

Results of the present research are comparable to those reported by others from long-term experiments and field studies. For example, [19] observed that the minimal SOC

**Fig. 3** Crop yield response to changes in soil organic carbon stock across the Huang-Huai-Hai plains



stock for achieving high crop yield of  $15 \text{ Mg ha}^{-1}$  in the HHH is  $24.5 \text{ Mg ha}^{-1}$  ( $15 \text{ g kg}^{-1}$  of SOM). In comparison, [27] estimated the SOC stock for high crop yield in HHH at only  $19.5 \text{ Mg ha}^{-1}$ , and [29] reported the stable value of SOC stock in Xuzhou experiment at  $25.0 \text{ Mg ha}^{-1}$  (almost  $15 \text{ g kg}^{-1}$  of SOM). The minimum threshold level of  $7.54 \text{ g kg}^{-1}$  of SOC concentration ( $13.0 \text{ g kg}^{-1}$  of SOM) from field investigations has been reported to achieve the crop productivity of  $15.0 \text{ Mg ha}^{-1}$  in the HHH [27]. In contrast, these results differ from the threshold level of  $15.0 \text{ Mg ha}^{-1}$  ( $10 \text{ g kg}^{-1}$  of SOM) across the region for fluvo-aquic *Inceptisols* reported by [Li et al. [14]].

Therefore, the synthesis of available data indicates that the threshold value of SOC stock in response to crop yield ranged from  $25.0$  to  $41.0 \text{ Mg ha}^{-1}$  in the root zone across the HHH, and the corresponding potential of increase in crop yield from  $12.8$  to  $18.0 \text{ Mg ha}^{-1} \text{ year}^{-1}$ . Although, the magnitude of yield response to SOC stock differs among fertilizer rate and soil types, increasing crop yield by improving SOC stock is a win–win and a sustainable strategy across the HHH.

#### The Limits of Available Data for the Results

The available data from experimental sites and published papers in the HHH region were collected and synthesized for detail analysis. Yet, it is difficult to collect all the data for similar application rate of N, P, K from the ten long-term experiments, because objectives of individual experiment differed among agro-ecosystems. However, the grouping of fertilizer managements based on the different rate of fertilizer application (e.g., CK, UF, CF, and INM) comprises four principal patterns of fertilizer managements adopted by households across the HHH region (Dont et al.,

2010). Nonetheless, there exists a lack of UF fertilizer management in Hengshui A, B, and Yucheng; CF management in Mengcheng; INM in Hengshui B; and Mengcheng. Furthermore, the data series are not similar for the same fertilizer management in different experimental sites across the HHH region.

Thus, the data presented in this article provide the general and uniform trends of crop yield response to increase in SOC stock for different fertilizer treatments and soil types across the HHH region. These results support the hypothesis and conclusions presented in this article. The data presented here also support the conclusion that depleted SOC stock can be restored, and agronomic yields can be increased by the adoption of INM across the HHH. However, additional research is need to establish response of crop yield to specific application rate of N, P, K in different soil types in the HHH.

#### Conclusions

Achieving food security is the greatest challenge facing China, because of the finite arable land resources and numerous competing demands. Thus, increasing crop yields by improving soil quality through increase in SOC stock is an important strategy. The data presented support the following conclusions: (i) response of crop yield to SOC stock differs among fertilizer management, soil types, and site-specific parameters, (ii) crop yield increases with increase in SOC stock for all long-term sites, (iii) in comparison with a rapid yield response by application of chemical fertilizers, increase in SOC stock and improvements in soil quality result in a gradual but sustainable yield increase over a long time duration, and (iv) the crop

yield increases with increase in SOC stock upon conversion from either none or unbalanced fertilizer management to INM. Restoration of the depleted SOC stock by conversion to a restorative land use and adoption of INM across the HHH can enhance soil quality and improve agronomic production. Crop yield can be increased by improving the SOC stock through strategies such as cropland planning, site-specific practices, *modus operandi*, and appropriate incentives.

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