Journal of Agricultural Science; Vol. 4, No. 12; 2012
ISSN 1916-9752 E-ISSN 1916-9760
Published by Canadian Center of Science and Education

Soil Organic Carbon Stock and Crop Yields in Huang-Huai-Hai Plains, China

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Received: August 28, 2012 Accepted: September 13, 2012 Online Published: November 15, 2012

doi:10.5539/jas.v4n12p140 URL: http://dx.doi.org/10.5539/jas.v4n12p140

Abstract

The Huang-Huai-Hai-plains (HHH) is the main wheat (*Triticum aestivum*)-maize(*Zea mays*) production area of China. Therefore, adoption of appropriate fertilizer management strategies of improving soil organic carbon (SOC) and crop yields is an important option in HHH. These studies included a total of 6 land use and management treatments including: (i) no fertilizer(CK); (ii) chemical nitrogen(N), phosphorus(P) and potassium(K) fertilizers separately(UF); (iii) combined application of chemical fertilizer N,P and K(CF); (ⅳ) wheat and maize straw retention or manures including that from soybean (*Glycine max*) cake, chicken, horse and cow dung or manures only (O); (ⅴ) combined application N, P and K and organic fertilizers (CFO); (ⅵ) combined application of chemical fertilizer N,P or K separately and organic fertilizers (UFO). The data indicated the following: (i) The baseline SOC stock of arable land was 18.9±1.8 Mg ha^{-1} and the corresponding crop yield was 4.4±1.5 Mg ha^{-1}; the highest SOC stock was 24.6±1.8 Mg ha^{-1} for CFO and the corresponding crop yield was 9.7±3.2 Mg ha^{-1}; (ii) The rate of increase of SOC stock was in the order of CFO>UFO>CF>O>UF, while that of increase in crop yield was in the order of CFO>CF>UFO>UF>O; (iii) Crop yield increased (Mg ha^{-1} yr^{-1}) by 0.114 in UF and CF, by 0.039 in treatment O,CFO and UFO, and by 0.033 in CK by increase in SOC stock by 1 Mg ha^{-1}; (ⅳ) Yield increased (Mg ha^{-1} yr^{-1}) by 0.298, 0.119,0.065, and 0.022 by over 5, 10, 15, and over 25 years by increase in SOC stock by 1 Mg ha^{-1}. Therefore, the combined application of chemical and organic fertilizers is the best choice for the developing countries to adapt to and mitigate climate change while advancing food security.

Keywords: crop yield, soil organic carbon stock, crop yield response to soil organic carbon, Huang-Huai-Hai plains, China, food security

1. Introduction

The challenges of mitigating climate change and ensuring global food security are among the main global issues of the 21 century. Anthropogenic activities have led to an increase in atmospheric concentration of Carbon Dioxide (CO_2) from 280 ppm in the per-industrial era to almost 400 ppm at present (The Carbon Dioxide Information Analysis Center [CDIAC], 2009; The World Meteorological Organization [WMO], 2008), and CO_2 concentration is increasing at the rate of about 2.2 ppm yr^{-1} . Yet, there are more than 1 billion food-insecure people on the world, mostly in developing regions of Asia/Pacific, Sub-Saharan Africa, South/Central American, and the Caribbean (The Food and Agriculture Organization [FAO], 2009). Consequently, mitigating climate change and increasing food production (Huang et al., 2002) are among the principal challenges. The strategy is to increase agricultural production without increasing either the land area or the chemical fertilizer used. Therefore, sustainable management of fertilizers is the optimal choice for the developing countries to adapt to and mitigate climate change while advancing food security.

China is the world's most populous country and a major emitter of greenhouse gases (GHGs) (Piao, et al., 2009). It is currently facing the dilemma of climate change mitigation caused by a strong increase in GHG emissions due to a rapid industrialization (Kong, et al., 2006; Kong & Zhang, 2008), and the increasing food demands to feed 22% of the world's population but with only 7% of the world's arable land area. Thus, identification of rational fertilizer management for achieving a continuous increase in crop yield and soil organic carbon (SOC) stock are important to China's food security and to mitigating climate change.

There is a strong relationship between agronomic production and the SOC stock, especially in low-input agriculture (none or low rate of fertilizer input) (Lal, 2010a,b). The effects of increase in SOC stock on increase in crop yield have been widely reported (Ganzhara, 1998; Petchawee et al., 1995). The data from Australia indicated a decline in yield of wheat with depletion of the SOC stock and increase in yield with accretion of the SOC stock, and a stable yield of ~2.75 Mg ha^{-1} with a steady state level of the SOC stock (Farquharson et al., 2003).Thus, an optimal level of the SOC stock is an essential determinant of high and sustained agronomic yield.

The Huang-Huai-Hai plains (HHH) region comprises of about 16% of the China's arable land, and it plays an important role in sustaining food security and mitigating GHG emissions. 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 in China (Liu et al., 2010). It is China's principal crop production area (Harris, 2004).The predominant cropping system in the region is the double-cropping of winter wheat and summer maize. However, the application of the amount of chemical fertilizer exceeds that of organic manure (Lei, 2005). Many farm households do not avail benefits of using the organic manure towards sustainable use of arable land. Yet, use of organic manure has been the traditional practice of maintaining soil quality in China over millennia (Bi et al., 2009). Thus, it is important to assess the impacts of different fertilizer management on agronomic yield, change in SOC stock, and on crop yield under long-term fertilizer management practices.

Collation, review and synthesis of the available research information on this topic for the HHH are relevant. Zheng et al. (2007) reported an increase of 81.1% in crop yield with the combined use of residues retention and chemical fertilizers. Cui (1997) reported that yields of wheat and maize were the highest and most stable with the balanced application of chemical N, P and K fertilizers. However, separate application N, P and K as chemical fertilizers did not increase the SOC stock. Thus, use of organics is essential to enhancing the SOC stock and increasing crop yield. Yan and Wei (2010) reported that the long-term use of organic fertilizer contributed to SOC sequestration by improving root development, but the contribution of balanced chemical fertilizers to agronomic yield was higher than that of organic fertilizers. Experiments conducted in other regions of China have also indicated a possible impact of increase in SOC stock on improvements in crop yield (Meng et al., 2000; A. J. Zhang & M. P. Zhang, 2001). The beneficial impact of a higher SOC stock on cereal yield at national level has been reported by Pan (2008) and Wang et al. (2010). The research conducted in individual experiments with a long-term application of organics and chemical fertilizers show that the increase in SOC stock mainly depends on the amount of organic manure used, and the increase in crop yield mainly depends on the balanced use of chemical fertilizers. So far, there is a lack of data relating increase in SOC stock and crop yield for different fertilizer management across the HHH. Furthermore, there is a lack of data relating temporal patterns of crop yield in relation to SOC stock under different fertilizer managements. Thus, the objectives of this study are to: (1) determine effects of different land use and managements on SOC stock and crop yield, (2) quantity the relationship between SOC stock and crop yield under different fertilizer managements, and (3) identify sustainable fertilizer management options which enhance SOC stock and increase agronomic production across the entire HHH region.

2. Data and Methods

2.1 Study Area and Soil Sampling

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) (Figure 1). This is the largest plain and constitutes an important agricultural region in China. The region covers 320,000 km^2 of an area comprising 18.67 million ha (M ha) of farmland and a population of 200 million (Liu et al., 2010). The northern latitude ranges from 32°00′ to 40°30′, and the eastern longitude ranges from 113°00′ to 118°00′ (Shi, 2003). The region is characterized by intensive use of irrigation and chemical fertilizers, and the predominant cropping system in the region is double-cropping of winter wheat and summer maize. The SOC concentration was measured for soils from different long-term experimental sites in the HHH (Figure 1).

Climate and soil properties of sites are shown in Table 1. The annual rainfall ranges from 461.9 to 837.3 mm, the annual accumulative temperature from 4874.0 to 5368.2 degree days, and the annual average temperature from 12.8 to 14.6℃(Lei, 2005).

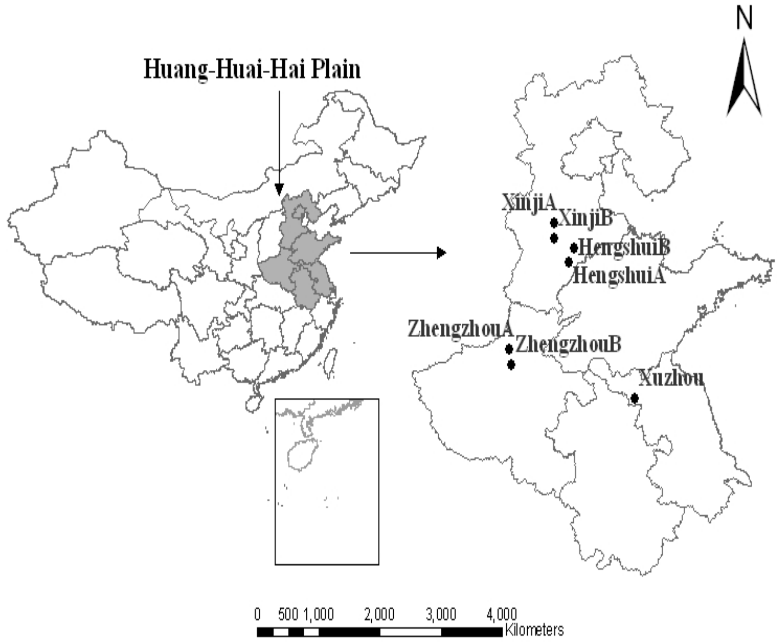

Figure 1． The location of seven long-term experimental sites

Table 1. Soil and climate environments of the 7 long-term experimental sites in the HHH

Sites	Location		Annual rainfall	Annual cumulative temperature	Annual average temperature	Experimental duration	Soil Properties		
							pH	Soil texture	Bulk density
County	Latitude	Longitude	Mm yr^{-1}	degree days	℃	year			Mgm^{-3}
Henshui A	37°42′	115°42′	478.1	4996.3	13.2	1979-2002	8.3	loam	1.4
Henshui B	37°43′	115°43′	478.1	4996.3	13.2	1979-2002	8.2	loam	1.5
Xinji A	37°54′	115°13′	461.9	5015.7	13.2	1979-1999	8.3	silt loam	1.4
Xinji B	37°55′	115°14′	461.9	5015.7	13.2	1979-1999	8.2	silt loam	1.4
Zhenzhou A	34°46′	113°40′	623.2	5334.0	14.4	1980-2000	8.1	loam	1.5
Zhenzhou B	34°47′	113°41′	623.2	5334.0	14.4	1990-1999	8.3	loam	1.5
Xuzhou	33°54′	117°57′	837.3	5368.2	14.6	1980-1987	8.3	sand loam	1.4

Soil samples for assessing the SOC concentration were obtained from 0-20 cm depth for all sites before harvest of wheat every year between 1980 and 2005. These soil samples were selected to analyse the SOC concentration. The SOC concentration was determined by the wet combustion method (Tiessen & Moir, 1993), bulk density by the core method (The core was 5 cm in diameter, 5 cm deep, and 100 cm^3 volume (Soil Survey Staff [SSF], 1999), and texture by the hydrometer method (Gee & Bauder, 1986). Soil texture ranged from silt clay loam, loam, silt loam to loam ([SSF], 1999). Crop rotation involved winter wheat and summer maize in XinjiA, XinjiB, ZhengzhouA, ZhengzhouB, HengshuiA, HengshuiB and Xuzhou cities. Grain yields were measured at harvest.

2.2 Experiments Designed and Management

The seven long-term experiments had different fertilizer treatments, and the rate of application of chemical fertilizer N, P, K and organic manure in these treatments (Table 2) were designed, according to the local household fertilizer managements and the soil nutrients across the different soil types in the HHH. Experimental plot number varied from 1 to 3 for every treatment across the long-term experiments, and the plot area varied from 40 to 100 m^2 (Zhang et al., 2005; Guo et al., 1998; Xia et al., 2008; Zhang et al., 2002; Lin et al., 2009).

Table 2. Application of chemical fertilizer and organic manures under different land use and management treatment

Treatments	C(Mg ha^{-1})	N (Mg ha^{-1})	P_2O_5(Mg ha^{-1})	K_2O(Mg ha^{-1})
CK	0	0	0	0
	0	0.135-0.360	0	0
UF	0	0	0.060-0.150	0
	0	0	0	0.060-0.150
CF	0	0.135-0.360	0.060-0.150	0.060-0.150
O	0.50-4.05	0.012-0.120	0.012-0.170	0.030-0.200
UFO	0.50-4.05	0.147-0.480		
	0.50-4.05		0.072-0.320	
	0.50-4.05			0.090-0.350
CFO	0.50-4.05	0.147-0.480	0.072-0.320	0.090-0.350

The application amount of fertilization under different treatments was calculated and synthesize based on experimental design in eight experimental sites.

All farm operations were the same except for the fertilizer managements described above. Winter wheat was irrigated 2 to 3 times and maize was irrigated 1 to 2 times depending on the precipitation distribution during the season (Li et al., 2007). The volume of water used for each irrigation was 900 (9 cm) to 12,00 (12 cm) m^3 ha^{-1}. Herbicides and pesticides were applied to control weeds and reduce insect pressure, respectively (Xia, 2007). Organic and chemical fertilizers including P and K were applied as basal dose, 1/3 to 2/3 part of N was applied as basal dose and the other part was top dressed for wheat and all chemical fertilizers were top dressed for maize (Zhang et al., 2005; Guo et al., 1998; Xia et al., 2008; Zhang et al., 2002; Lin et al., 2009).

2.3 Data Treatment and Calculation

For the purpose of macro-level study, all the treatments are grouped into six land use and managements based on different fertilizer managements at 7 experimental sites in the HHH (Table 2). Six land use and managements evaluated were: (i) no chemical fertilizer use or organic manure application as the control treatment (CK); (ii) chemical N, P and K fertilizers applied separately and without organic manure (UF); (iii) combined application of chemical fertilizer N,P and K without organic manure (CF); (iv) wheat and maize straw retention or manures including that from soybean cake, chicken, horse and cow dung or manures only (O); (v) combined application of chemical fertilizer N,P and K and organic fertilizers (CFO); (vi) combined application of chemical fertilizer N, P or K separately and organic fertilizers (UFO).

Different fertilizers managements at 7 experimental sites were grouped into chemical fertilizers and organic manure, but amounts of chemical fertilizer and organic manure applied were not the same for the six categories described above. The application rates ranged from 0.090 to 0.360 Mg ha^{-1} for N, from 0.060 to 0.150 Mg ha^{-1} for P and 0.0825 to 0.250 Mg $ha^{-1}$for K. The amount of organic fertilizers used also varied among 7 experimental sites (Table 2). Organic manure fertilizers were converted into C, N, P and K, according to the ratio of C:N and C:P for different organic manures (Lei, 2005). Nutrient application rate ranged from 0.012 to 0.120 Mg ha^{-1} of N, 0.012-0.170 of P, and 0.030 to 0.200 Mg ha^{-1} of K as organic fertilizers among all the experimental sites.

The data on SOC concentration (Table 3) were normalized and converted to SOC stock (Li et al, 2007) by using equation 1:

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

Where, SOC concentration is in g kg^{-1}, and soil bulk density (SBD) is in Mg m^{-3}, change in SOC stock in different treatments was computed with reference to the control (CK) and antecedent value by using equation 2:

$$\triangle SOC\ (Mg\ ha^{-1})=SOC_t - SOC_{CK} \quad (2)$$

Where, △SOC is the change in SOC stock, SOC_t refer to SOC stock in a specific treatment (CF, UF, O, CFO and UFO), SOC_{CK} is the SOC stock under control, change in crop yield in treatments was calculated using equation 3 :

$$\triangle Y(Mg\ ha^{-1})=Y_t\text{-}Y_{CK} \quad (3)$$

Where, △Y is the change in crop yield, Y_t refer to crop yield in a specific treatment (CF, UF, O, CFO and UFO), Y_{CK} is the crop yield under CK control. The productivity of the effects of SOC stock and that compared with CK were calculated using equation 4 :

$$Y_p = \triangle Y/\triangle SOC \quad (4)$$

Where, Y_p is the productivity of SOC stock in different treatments compared with CK. The annual crop yield response to SOC stock concentration change (YRS) was calculated using equation 5:

$$YRS\ (Mg\ ha^{-1}\ 1Mg\ SOC\ year^{-1})=(\triangle Y_I \div \triangle SOC_I)/d \quad (5)$$

Where, d is the experimental duration in years.

Table 3. Statistical analysis SOC stock and crop yield in different fertilizer managements

Treatments	N	SOC stock ($Mg\ ha^{-1}$)		Crop yield ($Mg\ ha^{-1}$)			
		Mean	Standard deviation	Mean	Standard deviation	Minimum	Maximum
CF	204	20.8c	2.1	9.4e	2.9	1.8	15.9
O	107	20.3bc	2.5	5.5b	2.4	2.0	11.9
UF	172	19.7ab	1.7	6.2c	2.7	1.4	13.6
CFO	282	24.3d	6.6	9.7e	3.2	1.9	17.4
UFO	238	23.4d	7.2	7.6d	3.5	2.1	16.0
CK	110	18.9a	1.8	4.4a	1.5	1.7	7.8
Total	1113	21.8	5.3	7.7	3.5	1.4	17.4

Mean followed by difference letter differ from one another at 5% level of probability.

2.4 Data Processing and Statistics

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

3. Results and Discussions

3.1 The Crop Yield and SOC Stock in Different Land Use and Managements

Mean crop yield under different land use managements from 1978 to 2005 are shown in Table 3. The mean crop yield for CFO, UFO, CF, UF and O differed significantly from that of the CK. Crop yield for different land use and managements ranged from 4.4±1.5 to 9.7±3.2 Mg ha^{-1}. The highest crop yield was measured for the CFO followed by that for the CF. Expectedly, the lowest crop yield was obtained in the CK. The crop yield was in the order of

CFO>CF>UFO>UF>O>CK. The data presented show that crop yield was strongly impacted by the use of combined chemical fertilizers than the use of organic manures.

The mean SOC stock for CFO, UFO, CF, UF and O differed significantly from that for the CK (Table 4). The SOC stock for different land use and managements ranged from 18.9±1.8 to 24.3±6.6 Mg ha^{-1}. The SOC stock in CFO was the highest among all the managements, followed by that for UFO, and the least for CK. The SOC stock was in the order of CFO>UFO>CF>O>UF>CK. Thus, the combined use of chemical fertilizers and organic manures has the highest technical potential of SOC sequestration.

Table 4. Descriptive statistics of SOC in different fertilizer managements

Treatments	N	SOC（Mg ha^{-1}）			
		Mean	Standard Deviation	Minimum	Maximum
CF	204	7.2b	0.6	5.5	8.6
O	107	7.2b	0.8	5.5	10.0
UF	172	6.9ab	0.5	5.7	8.1
CFO	282	8.5c	2.4	6.0	20.6
UFO	238	8.3c	2.6	5.5	19.4
CK	110	6.6a	0.6	5.2	8.0
Total	1113	7.7	1.9	5.2	20.6

Mean followed by difference letter differ from one another at 5% level of probability.

The results show that the combined use of organic manure and chemical fertilizers for CFO improved crop yield and SOC stock more than that by other land use and managements across the HHH. The results are similar to that of the experimental conducted in Fengqiu site in the HHH (Gong et al., 2009) and in India (Kukal et al., 2009). An increase of 28.6% in SOC stock for CFO was less than the maximum increase by 58.0% in Fengqiu (Gong et al., 2009). The reason is that the SOC under CFO across the HHH varied with soil types. The results also show that the fertilizer management combined chemical and organic fertilizer is the best way to increase crop production and improve SOC sequestration across the HHH.

The SOC stock and crop yield for CK was 18.9±1.8 Mg ha^{-1} and 4.4±1.5 Mg ha^{-1}. Taking into consideration the effects of double cropping, the mean crop yield of 2.2 Mg ha^{-1} for CK treatment is similar to the global average cereal yield in 1980 (Lal, 2010a). This case study shows that the long-term and widespread use of extractive farming practices, similar to fertilizer management for CK across the HHH, can't support high crop yield. It has been documented that black soil (Mollisols) of northeast China have lost 50% of their antecedent SOC stock (Yu et al., 2006), probably because of low rate of fertilizer use, and thus by nutrient mining(Lu et al., 2009).

The SOC stock and crop yield for CF were 20.8±2.1 Mg ha^{-1} and 9.4±2.9 Mg ha^{-1}, respectively. Such a trend indicates that crop yield can be drastically improved with the application of combined N, P and K chemical fertilizers, yet, the increase in SOC stock was lower than that in CFO and UFO. The instant increase in crop yield encouraged the household to apply much more chemical fertilizers to the cropland to maximize the output (Zhang et al., 2004; Kong et al., 2009). However, fertilizer management for CF treatment neither improved SOC stock to a higher level nor sustained soil quality. Thus, fertilizer management for CF treatment is not the best way to sustain high crop production and enhance SOC sequestration compared with CFO treatment.

With regard to O , increase in crop yield was only higher than that for CK, and the absolute increase in SOC stock was lower than that for UFO, CFO, UF and CF. These results are not in accord with rapid and strong increases in SOC stock reported in Fenqiu county(Gong et al., 2009). The traditional fertilizer management has no advantage over CF, CFO, and UFO treatments, which lead to the shift of a household from organic manure to chemical fertilizers.

Fertilizer management for UF and UFO treatments is an example of the unbalanced fertilizer management across the HHH. The effects of increase in crop yield and SOC stock were intermediary. In fact, there are some farmers who have only small parcels of land and use this type of fertilizer management, because of poor knowledge about soil quality and fertilizer management. Thus, the potential of increasing crop yield and SOC stock sequestration is high compared with fertilizer management involving CFO treatment.

The data show that SOC stock and crop yield were strongly impacted by fertilizer management. Therefore, judicious use of chemical fertilizers and organic manure is an important strategy to sustaining high crop production and enhancing SOC sequestration across the HHH croplands.

3.2 Crop Yield Response to SOC Stock in Different Land Use and Managements

The trends of change of crop yield in response to increase in SOC stock for different managements across the HHH are not similar across the entire region (Figure 2). The data indicate that the SOC stock and crop yield can be strongly increased by CFO and UFO treatments compared with other managements.

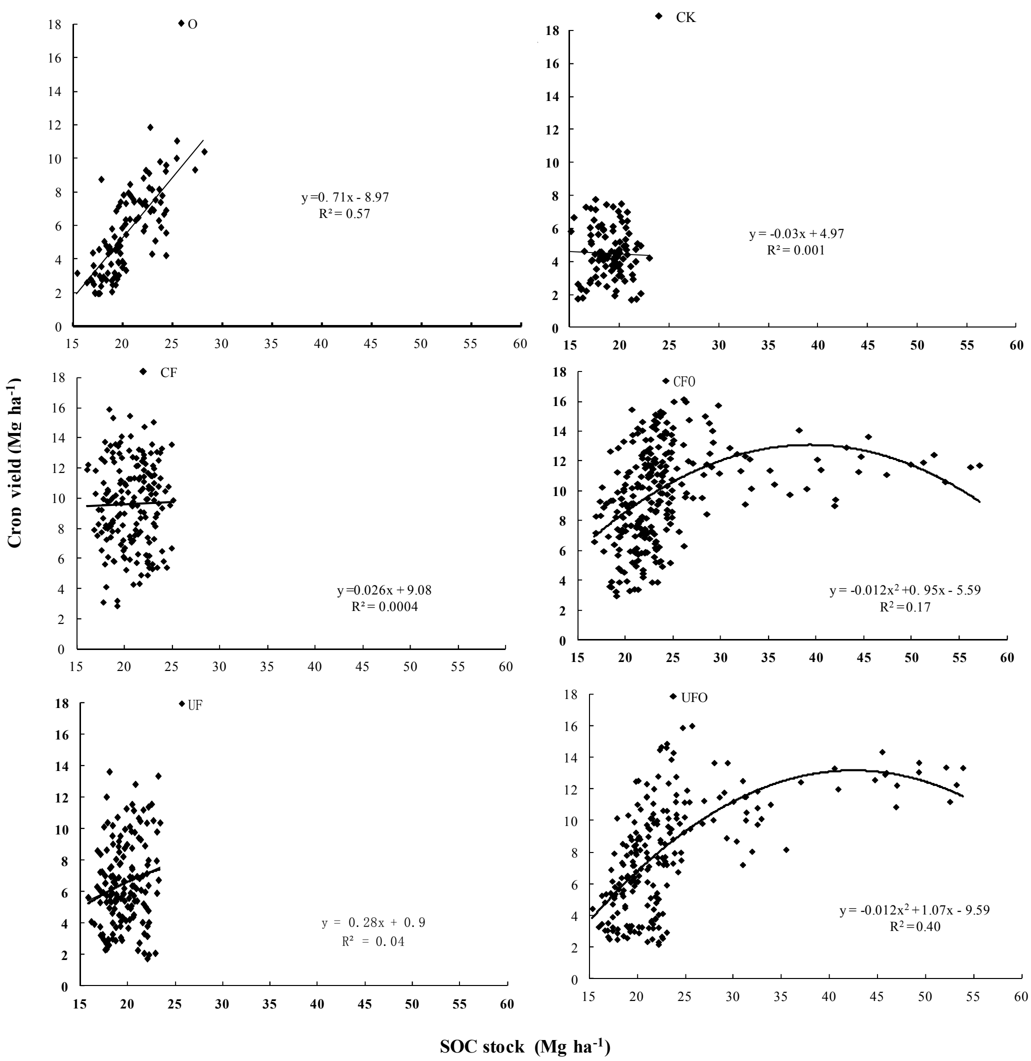

Figure 2. Crop yield response to SOC stock in different fertilizer treatments

There was a linear trend of change in crop yield response to increase in SOC stock for CK, O, UF, CF, UFO and CFO (Y=0.75x-8.7; R^2 = 0.57; x is the SOC stock in Mg ha^{-1} for different land use managements, Y is the crop yield in Mg ha^{-1}) across the HHH (Figure 3). On average, crop yield increased by 0.033 Mg ha^{-1} yr^{-1} by increase in SOC stock by 1 Mg ha^{-1} across the HHH over 25 years. The crop yield response to increase in SOC stock for the CF was above the linear trend line, it increased crop yield more than the increase in SOC stock. There were a sharp linear trends of change in crop yield response to increase in SOC stock for chemical fertilizer treatments UF and CF (Y=2.63x-45.447, R^2=0.99), and for O, CFO, UFO (Y=0.89x-12.565, R^2=0.95). Crop yield increased by 0.115 Mg ha^{-1} yr^{-1} in chemical fertilizer treatments UF and CF, and by 0.039 Mg ha^{-1} yr^{-1} in O, CFO and UFO fertilizer managements by increase in SOC stock by 1 Mg ha^{-1} over 25 years. The incremental increase in crop yield by increase in SOC stock was higher than the average reported by Lal (2010b). This difference in response may be due to the low antecedent SOC stock before 1980s (Shi, 2003).

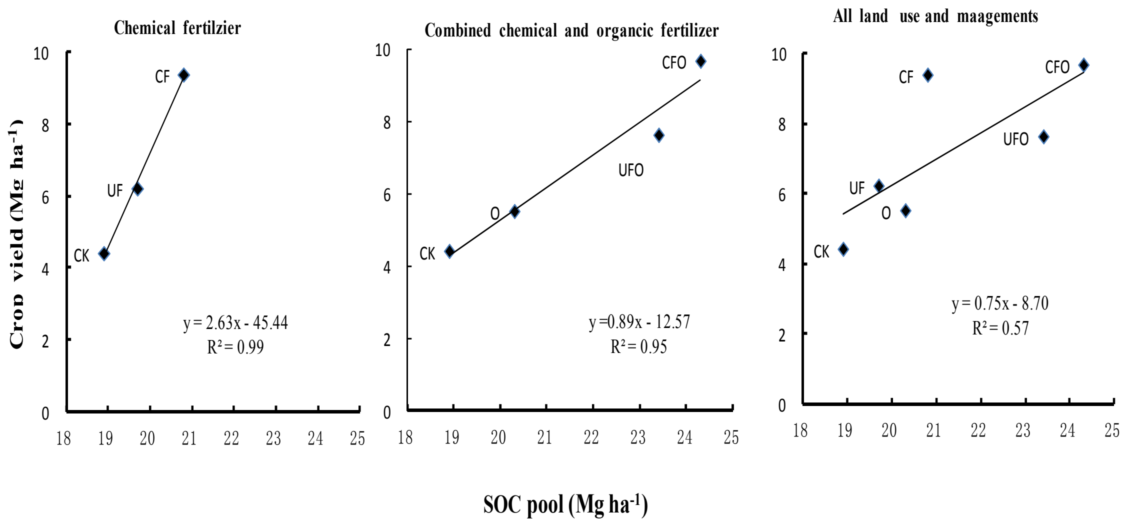

Figure 3. Regression equations relating crop yield response to increase in SOC stock

An optimal level of the SOC stock is an essential determinant of soil quality to support the relatively high crop yield (Lal, 2010a). The data presented show that there exits strong relationship between agronomic production and the SOC stock across the HHH. The potential increases in crop yield and SOC stock are even higher. Furthermore, different fertilizer managements have different effects on SOC stock and crop yield. Although, Increase in crop yield was high by application of chemical fertilizers, especially CF, but the increase in SOC stock is rather gradual. However, both the crop yield and SOC stock increased by combined application of chemical and organic fertilizers (CFO), and SOC stock increased strongly, while the crop yield increased gradually for O treatment compared with other fertilizer management. These data indicate that the dilemma of mitigating climate change and ensuring food security can both be addressed by the combined application of chemical and organic fertilizers.

3.3 Crop Yield Response (YRS) to SOC Stock Compared with CK

The data on YRS, increase in crop yield and SOC stock for different fertilizer managements compared with CK, are shown in Table 5. Some important indicators are incremental increase in crop yield with unit increase in SOC stock (Mg ha^{-1} yr^{-1}, rate of increase of SOC stock (%)), and the rate of increase in crop yield (%).

Table 5. Statistical analysis of YRS, SOC and crop yield increase in different fertilizer managements

Treatments	△SOC (Mg ha^{-1})	SOC increase (%)	△Y (Mg ha^{-1})	Crop yield increase (%)	Yp (Mg Mg^{-1} ha^{-1})	YRS (Mg Mg^{-1} ha^{-1}yr^{-1})
CF	1.9b	8.7c	5.0d	50.6d	2.7	0.116
O	1.6b	7.2c	1.7b	25.3b	1.1	0.047
UF	0.8b	3.8b	1.7b	21.2b	2.2	0.094
CFO	5.4c	19.0e	5.2d	51.4d	1.0	0.042
UFO	4.8c	16.1d	3.4c	38.7c	0.7	0.031

Mean followed by difference letter differ from one another at 5% level of probability.

Increase in the SOC stock for CF, O, UF, CFO and UFO treatments in the root zone by 1 Mg C ha^{-1} increased cumulative yield (Y_p) of crops in the HHH compared with CK by 2.67, 1.078, 2.15, 0.96 and 0.7 Mg yr^{-1}, and the rates of increase (YRS) during the experimental period were 0.116, 0.047, 0.094, 0.042 and 0.031 Mg yr^{-1}, respectively. Increase in crop yield with increase in SOC stock by 1 Mg C ha^{-1} and rate of increase in yield were in the order of CF>UF>O>CFO>UFO>CK. These data, indicating that continuous application of chemical fertilizers can increase crop yield, are similar to those reported by Yan and Wei (2010).

Compared with CK, the SOC stock for CF, O, UF, CFO and UFO increased by 1.9, 1.6, 0.8, 5.4, and 4.8 Mg ha^{-1}, and the rate of increase in SOC stock was 8.7%, 7.2%, 3.8%, 19.0%, and 16.1%, respectively. Compared with CK, cumulative crop yield for CF, O, UF, CFO and UFO managements increased by 4.95, 1.68, 1.72, 5.22 and 3.36 Mg ha^{-1}, and the rate of increase in crop yield was 50.6%, 25.3%, 21.2%, 51.4% and 38.7%, respectively. The range of increase in SOC stock and crop yield were less than that reported by Yan et al. (2010), Cai and Qin (2006) and Cui (1997).

There were different levels of increase in SOC stock, crop yield and the incremental increase in crop yield. The order of treatments was CFO>UFO>CF>O>UF for increase in SOC stock, CFO>CF>UFO>UF>O for increase in crop yield, and CF>UF>O>CFO>UFO for incremental increase in crop yield per unit increase in SOC stock. The rate of increase of SOC stock and crop yield was similar to the individual experiment conducted in the HHH (Cui, 1997; Cai & Qin, 2006).

Differences in rates of increase in the crop yield and SOC stock indicate differential response of these variables to the application of fertilizers. Crop yield was sensitive to fertilizer use. However, the SOC stock was sensitive to application of organic manure at all levels. Therefore, the application of chemical fertilizers, especially the combined fertilizers, can increase crop yield rapidly when SOC stock is at an adequate level. These results support the conclusion that the both increase in crop yield and SOC stock are due to high external inputs in the HHH (Zhang et al., 2001). A previous study conducted in the Daxing in the HHH from 1982 to 2000 indicated that average SOC concentration increased from 5.7±1.1 to 7.3±1.6 g kg^{-1}, average wheat yield from 3.23 to 5.36 Mg ha^{-1}, and maize yield from 3.44 to 5.89 Mg ha^{-1} , with increase in fertilizer application rates from 0.429 to 0.513 Mg ha^{-1} (Kong et al., 2009). Therefore, combined application of chemical fertilizers and organic manure is essential to improving SOC stock. Further, maintaining an optimal level of SOC stock is a precondition to obtaining high crop yields across the HHH.

3.4 Temporal Pattern of SOC Stock, Crop Yield and Crop Yield Response to SOC Stock Change

The data on temporal change in crop yield and SOC stock for different fertilizer managements involving long-term experimental duration of 5, 10, 15 and more than 20 years are shown in Table 6, Figures 4 and 5. The trend of change in SOC stock can be divided into three groups. The SOC stock in group 1 including CK and O managements is stable over time, the mean SOC stock ranged from 18.5 to 18.7 Mg ha^{-1} for CK , and 19.6 to 20.4 Mg ha^{-1} for O. The SOC stock in group 2 including UF and CF treatments decreased slowly over time, while the SOC stock in group 3 including UFO and CFO progressively increased with the increase in duration. The data indicated that SOC stock increased by a continuous and combined application of chemical and organic fertilizers as in CFO and UFO managements. By these treatments, the SOC stock increased and was sustained at a higher level across the HHH.

Similarly, crop yields can also be divided into three groups. Group 1 consists of crop yields in O and UF managements, which decreased significantly with increase in experimental duration. Group 2 consists of crop yields in CF, CFO and UFO, which increased within 10 years, but decreased with increase in duration beyond 10 years. Group 3 consists of crop yield in CK which was low and stable, but decreased with increase in duration of the experiment.

Regression equations of temporal change in crop yield response to SOC stock are shown in Figure 6. The change in crop yield response to change in SOC stock follows a declining trend over time. Crop yield increased by 0.298 Mg ha^{-1} yr^{-1} in 5 years, by 0.119 Mg ha^{-1} yr^{-1} in 10 years, 0.065 Mg ha^{-1} yr^{-1} in 15 years, and 0.022 Mg ha^{-1} yr^{-1} in more than 20 years with increase in SOC stock by 1 Mg ha^{-1}. The data show that the rate of increase in crop yield declined over time.

Both SOC stock and crop yield declined in management without any fertilizer application. Similarly, the unbalanced use of individual N, P and K fertilizers decreased crop yield and SOC stock. In comparison, combined application of chemical fertilizers increased crop yield and SOC stock rapidly and continuously. The results presented confirmed that the increase in SOC stock in the HHH is due to the balanced application of chemical fertilizers N, P and K and straw residue returned since 1980s. Therefore, combined use of organic manure and chemical fertilizers as used in CFO and UFO managements increased SOC stock and crop yields by improving soil quality and resilience.

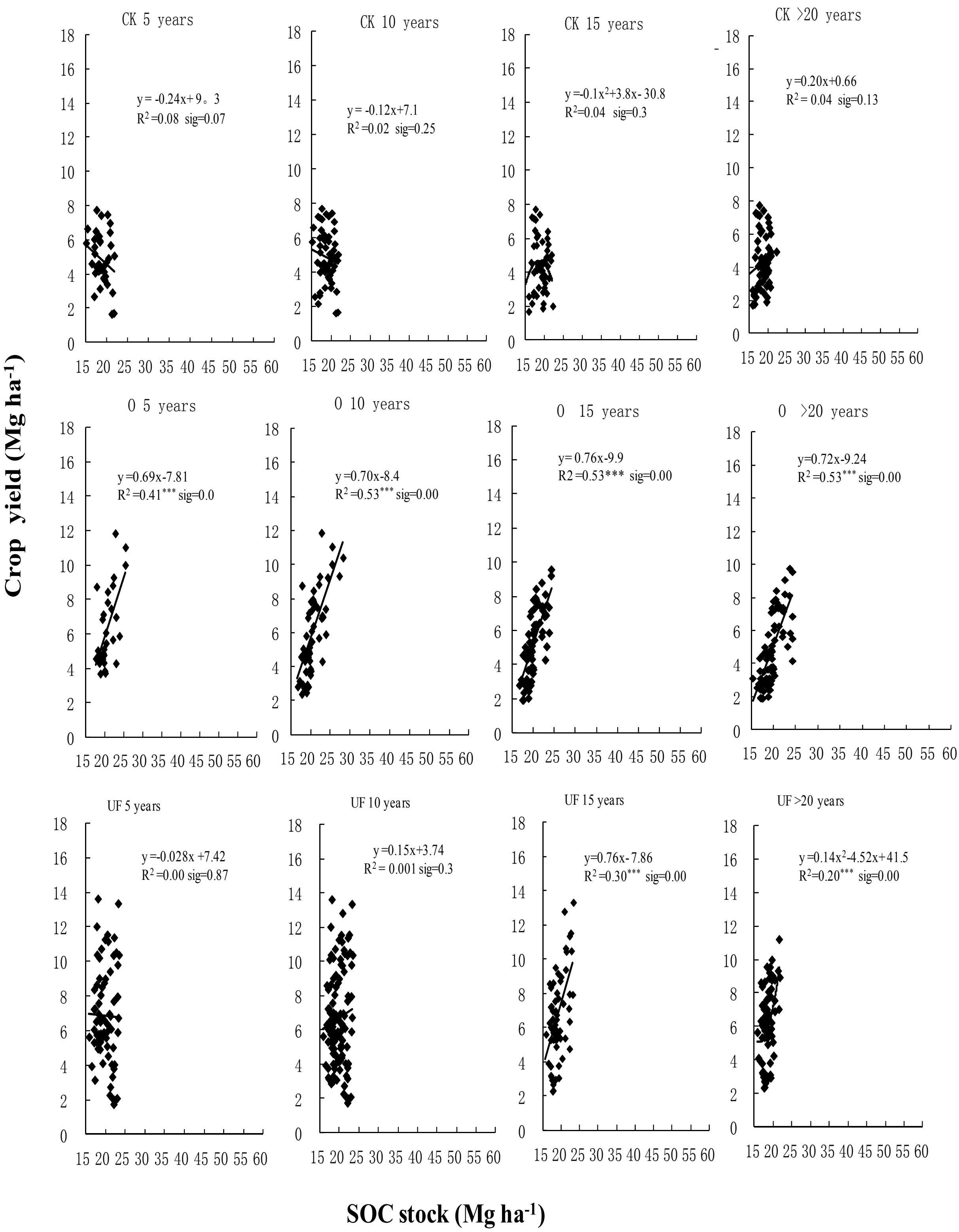

Figure 4. Temporal changes in crop yield response to increase in SOC stock for CK, O and UF treatments

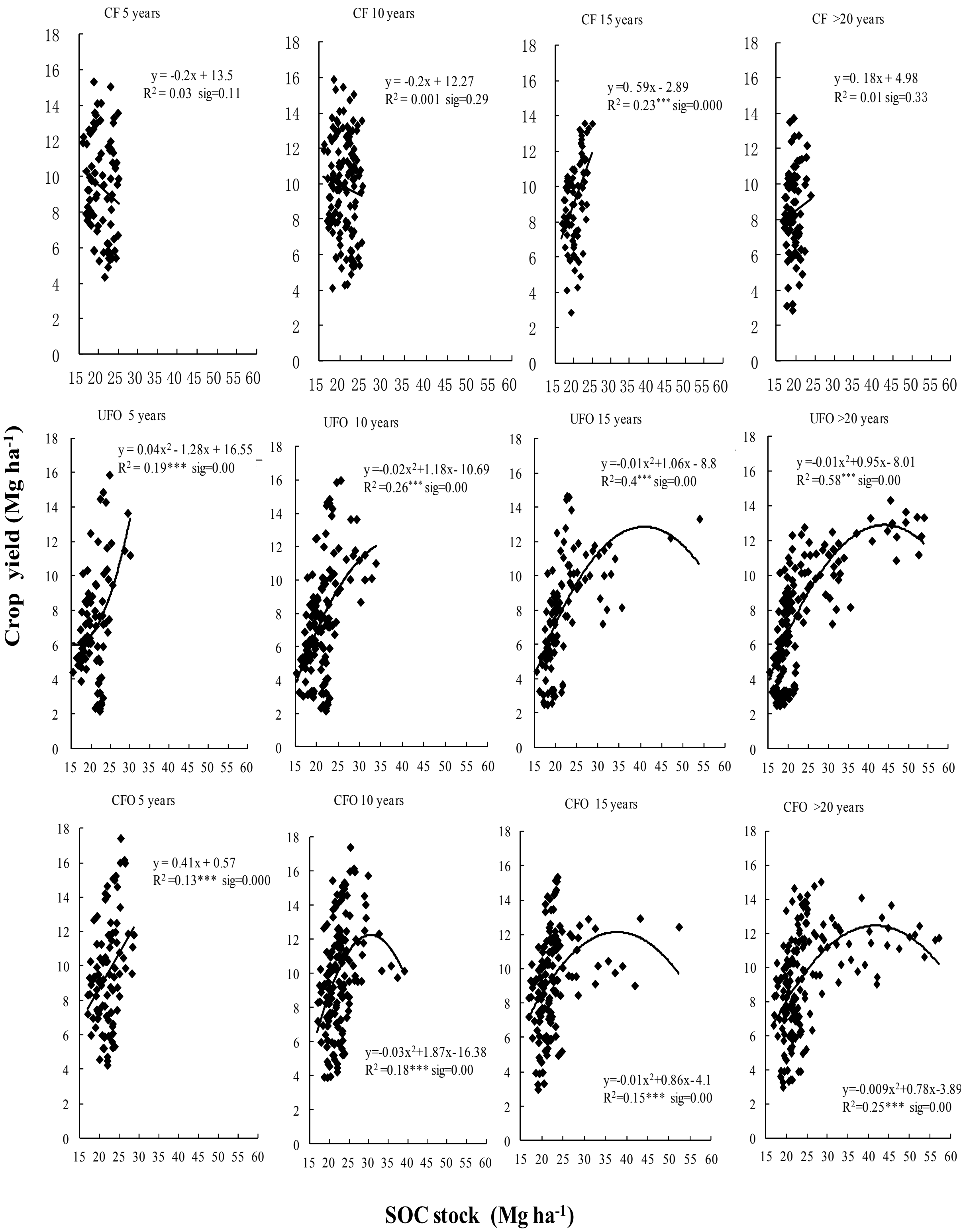

Figure 5. Temporal changes in crop yield response to increase in SOC stock for CF, CFO and UFO treatments

Table 6. Temporal change trend of crop yield response to SOC stock change in different fertilizer managements

Duration	Treatments	N	SOC(Mg ha^{-1})		Crop yield(Mg ha^{-1})	
			Mean	Standard. Deviation	Mean	Standard. Deviation
	CF	80	20.8c	2.6	9.4c	2.9
	O	35	20.3bc	2.0	6.1b	2.2
	UF	70	19.8b	2.0	6.9b	2.8
5	CFO	100	21.8e	2.6	9.5c	3.0
	UFO	85	20.8c	2.9	7.1b	3.1
	CK	41	18.7a	1.8	4.9a	1.5
	Total	411	20.6	2.6	7.8	3.2
	CF	130	20.7cd	2.2	9.8d	2.8
	O	57	20.4c	2.4	6.0b	2.4
	UF	113	19.6b	1.8	6.6b	2.8
10	CFO	162	22.5e	3.6	9.9d	3.1
	UFO	137	21.4d	3.5	7.5c	3.3
	CK	65	18.6a	1.8	4.9a	1.4
	Total	664	20.9	3.1	8.0	3.4
	CF	83	20.3b	2.0	9.2e	2.5
	O	68	20.1ab	1.9	5.3b	2.0
	UF	65	19.0a	1.8	6.6c	2.5
15	CFO	146	22.7c	5.0	9.3e	2.8
	UFO	115	21.8c	5.8	7.7d	3.0
	CK	58	18.8a	1.6	4.4a	1.5
	Total	535	20.9	4.2	7.6	3.1
	CF	78	19.5a	1.5	8.4cd	2.4
	O	82	19.6a	2.1	4.8a	2.0
	UF	75	18.5a	1.3	6.0b	2.2
>20	CFO	184	24.7b	8.0	9.1d	2.9
	UFO	153	23.9b	8.9	7.7c	3.2
	CK	65	18.5a	1.5	4.3a	1.5
	Total	637	21.9	6.8	7.3	3.2

Mean followed by difference letter differ from one another at 5% level of probability.

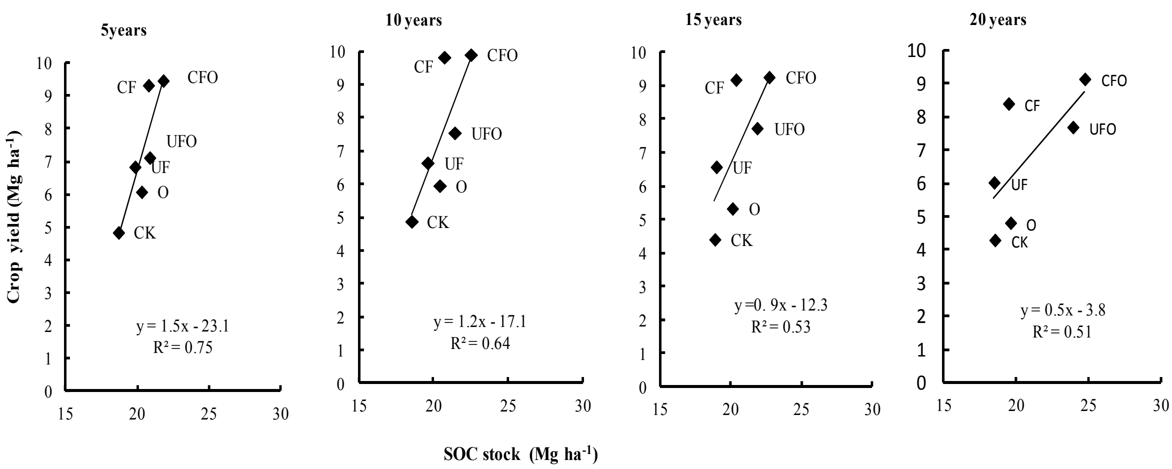

Figure 6. Temporal changes in crop yield response to increase in SOC stock

4. Conclusions

For the fertilizer management of CF and UF without application of organic manure, input of C was mainly those from roots, root exudates and retention of crop residues. Thus, the increase in SOC stock was less than that for CFO and UFO managements. For O, the increase in SOC stock and crop yield was also less than those for CFO and UFO, due to the lack of necessary nutrients.

Whatever, rational fertilizer managements, as was the case with CFO and UFO, can restore the SOC stock to high level and also improve agronomic productivity. Any substantial increase in SOC stock can only be achieved with long-term application of organic manures (biomass-C). The combined application of chemical and organic fertilizers, not only increased crop yield but also increased the external C inputs which contributed to increase in SOC stock. Thus, the SOC stock increased over time with the combined application of inorganic and organic fertilizers. These management increased SOC stock continuously and maintained it at a higher level along with the high crop yield. The examples of optimal fertilizer management across the HHH are CFO and UFO.

The sustainable fertilizer management, similar to those of CFO and UFO, can restore the SOC stock to above the threshold level and also improve crop yields. Therefore, the combined application of chemical and organic fertilizers is the best choice for the developing countries to advancing food security while mitigating climate change.

Acknowledgements

This work was supported by Special Fund for National Land Resource-scientific Research from National Ministry of Land and Resources, China (201011006-3), the Basic Research Development Program of China (973 Program, no. 2009CB118607), and the National Natural Science Foundation of China (Grant No. 40871254).

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