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Changes in cropland topsoil organic carbon with different fertilizations under long-term agro-ecosystem experiments across mainland China

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Topsoil soil organic carbon (SOC) data were collected from long-term Chinese agro-ecosystem experiments presented in 76 reports with measurements over 1977 and 2006. The data set comprised 481 observations (135 rice paddies and 346 dry croplands) of SOC under different fertilization schemes at 70 experimental sites (28 rice paddies and 42 dry croplands). The data set covered 16 dominant soil types found in croplands across 23 provinces of mainland China. The fertilization schemes were grouped into six categories: N (inorganic nitrogen fertilizer only), NP (compound inorganic nitrogen and phosphorus fertilizers), NPK (compound inorganic nitrogen, phosphorus and potassium fertilizers), O (organic fertilizers only), OF (combined inorganic/organic fertilization) and Others (other unbalanced fertilizations such as P only, K only, P plus K and N plus K). Relative change in SOC content was analyzed, and rice paddies and dry croplands soils were compared. There was an overall temporal increase in topsoil SOC content, and relative annual change (RAC, g $\mathrm{kg^{-1}\ yr^{-1}}$) ranged –0.14–0.60 (0.13 on average) for dry cropland soils and –0.12–0.70 (0.19 on average) for rice paddies. SOC content increase was higher in rice paddies than in dry croplands. SOC increased across experimental sites, but was higher under organic fertilization and combined organic/inorganic fertilizations than chemical fertilizations. SOC increase was higher under balanced chemical fertilizations with compound N, P and K fertilizers than unbalanced fertilizations such as N only, N plus P, and N plus K. The effects of specific rational fertilizations on SOC increase persisted for 15 years in dry croplands and 20 years in rice paddies, although RAC values decreased generally as the experiment duration increased. Therefore, the extension of rational fertilization in China's croplands may offer a technical option to enhance C sequestration potential and to sustain long-term crop productivity.

long-term agro-ecosystem experiments, fertilization, croplands, soil organic carbon, carbon sequestration, cross site analysis

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Soil carbon in the form of organic matter (soil organic carbon, SOC) is a primary ecosystem component and plays an important role in crop productivity [1]. SOC is also an important carbon reservoir that influences an ecosystem's carbon balance [2]. Recently, C sequestration in terrestrial ecosystems has been proposed as an important countermeasure under the Kyoto Protocol to mitigate increasing atmospheric greenhouse gases. As projected in the Fourth Assessment Report by the Intergovernmental Panel on Climate Change (IPCC AR4), soil C sequestration in croplands may constitute 90% of global biophysical potential for mitigating greenhouse gases in agriculture [3]. There have been

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many studies on soil organic carbon dynamics and the significance of C sequestration worldwide. Increases in soil organic carbon in China's croplands have been shown at national [4], provincial [5] and county scales, and via cross-site comparison of long-term agro-experimental sites [6]. Carbon sequestration and attendant SOC increases may offer a sound option to enhance crop productivity and to mitigate climate change effects on China's agriculture [7,8]. Understanding and estimating soil C sequestration has emerged as a research frontier of earth sciences and ecology in the context of global change. However, influences of crop management practices and soil and climate conditions should be addressed clearly when evaluating the potential of rational biophysical and technical C sequestration [9].

Agricultural management practices for improving crop productivity such as tillage, fertilization and irrigation have intense and short-term impacts on topsoil SOC contents. A large number of long-term agro-ecosystem experiments with tillage and fertilization treatments have been established across mainland China since the 1970s [10–14]. However, there have only been a few studies on the integrated impacts of these agro-management practices of China's cropland SOC dynamics, especially of different fertilization schemes on topsoil SOC storage at the national scale. This has prevented the assessment of crucial factors and the impact of fertilization on cropland SOC dynamics, and thus impeded addressing C sequestration potential under a sound fertilization scheme. In recent years, the role of SOC accumulation in rice productivity and interactions of multi-processes and mechanisms involved in rice paddy C sequestration were addressed using cross-site studies of long-term agro-ecosystem experiments from South China [15,16]. Overall effects of agro-management and crop production on topsoil SOC dynamics were analyzed using national cropland soil monitoring data [17]. More recently, a cross-site study of conservation tillage on topsoil SOC dynamics was conducted using long-term tillage experiments across China, and showed that a conservation tillage system with straw return and minimum tillage enhanced C sequestration and crop productivity in croplands [18].

To assess the overall impact of fertilization on topsoil SOC dynamics, and to address fertilization practices for enhancing crop productivity and C sequestration of China's croplands, an analysis was conducted of cropland SOC changes under long-term agro-ecosystems with fertilization treatments across China. We compiled a 70-site dataset of long-term experiments available in the literature, spanning a sample collection period from 1977 to 2006. We assessed dynamics by defining a relative annual change (RAC) in SOC from normalized data across the treatments at a single site. We also tested the difference in RAC between dry croplands (DCs) and rice paddies (RPs), and role of experiment duration in SOC changes was determined to investigate options for enhancing C sequestration and Chinese cereals production.

1 Materials and methods

1.1 Data source

Online databases, China's Academic Magazine and Weipu Science and Technology Literature, were searched for publications on long-term fertilization experiments. Site, soil type, crop and yield, experiment duration, fertilization schemes, and SOC contents were recorded. Available sites and treatments were selected for analysis which met the following criteria: (i) fertilization schemes were conducted consistently as inorganic, organic and combined chemical and organic/inorganic fertilizers, with other agro-management practices unchanged across the treatments; (ii) experiment duration was ≥6 years, with a known start year; (iii) a treatment of plot at least of 10 m^2; (iv) consistent SOC measurement protocol and initial and final SOC measurements clearly reported; and (v) a data from a control experiment site of no fertilization available. A data set from 76 publications was finalized describing 70 single long-term experimental sites (42 DCs and 28 RPs) covering 16 dominant soil types across 23 provinces of mainland China. There were 481 individual observations in total (346 in DCs and 135 in RPs) of SOC changes.

1.2 Data treatment

Fertilization schemes were grouped into six categories: (i) inorganic N only (N); (ii) compound inorganic N and P (NP); (iii) compound fertilization with inorganic N, P and K (NPK); (iv) organic fertilizer only (O); (v) combined inorganic/organic fertilizers (OF); and (vi) other unbalanced fertilization including N plus K, P plus K. Mass fertilizer application rate was converted to nutrient application rate using the nutrient contents in normal fertilizers. The mass application rate was in the range 24–1810 kg ha^{-1} for DCs and 17–3317 kg ha^{-1} for RPs.

Analysis of SOC changes was conducted using the following procedure: (i) Normalizing the original data. Conversion to SOC values was performed when soil organic matter data was available. This was done using a conversion factor of 0.58, assuming a mean composition of 58% C in soil organic matter. (ii) Calculation of mean annual SOC change under a single treatment through experiment duration. Annual change (g kg^{-1} yr^{-1}) in SOC under a single treatment was calculated using the following equation [4]:

$$\mathrm{AI}=(\mathrm{SOC}_t-\mathrm{SOC}_0)/t, \tag{1}$$

where AI is the mean annual change (g kg^{-1} yr^{-1}) within the experiment duration of t years, which is the difference between initial and final calendar year, SOC_0 and SOC_t are SOC measurement values of initial and final year of the experiment, respectively. (iii) Calculation of relative annual change under a certain fertilization scheme. To determine net influence of a single fertilization practice, temporal changes under no fertilization should be taken into account. A relative annual change (RAC, g kg^{-1} yr^{-1}) was defined and calculated by subtracting a change under a certain fertilization scheme (TR) from the control (CK) [4]:

$$RAC=((SOC_t-SOC_0)_{TR}-(SOC_t-SOC_0)_{CK})/t. \tag{2}$$

Simplified as:

$$RAC=AI_{TR}-AI_{CK}. \tag{3}$$

1.3 Data processing and statistics

Data were organized into DCs and RPs. All data were expressed as mean plus standard deviation. Data treatment and processing was conducted using Microsoft Excel 2003. Significance of differences at $P<0.05$ and $P<0.01$ between fertilization treatments, cropland types and experiment duration blocks were tested using TTEST and SPSS (Version 13.0).

2 Results and discussion

2.1 Distribution of SOC changes at the experimental sites

The distribution of annual SOC change under the single treatments is shown in Figure 1. Of the total 481 observations, 94% showed an increase and 6% a decrease in SOC. Overall annual change in SOC in the tested croplands ranged from –0.14 to 0.70 g kg^{-1} yr^{-1} with a mean of 0.15 g kg^{-1} yr^{-1}. As shown in Table 1, the range of annual change in dry cropland SOC was –0.140.60 g kg^{-1} yr^{-1} with a mean of 0.13 g kg^{-1} yr^{-1}, and for RPs –0.12–0.70 g kg^{-1} yr^{-1} with a mean of 0.19 g kg^{-1} yr^{-1}. Approximately 50% of total observations had an increase of 0–0.2 g kg^{-1} yr^{-1} for both DCs and RPs. A meta analysis of soil monitoring data showed an overall annual SOC increase of (0.076±0.219) g kg^{-1} in China's croplands in the period 1985–2006, with DCs specifically increasing by (0.056±0.200) g kg^{-1} and RPs by (0.110±0.244) g kg^{-1}. Our results here support the finding of an overall SOC increase in China's croplands [4]. The overall mean increase in SOC here is much higher than that found from soil monitoring data. Thus, fertilization treatments exerted a profound effect on SOC increase at the long-term experimental sites, with some variation in SOC response to different crops and treatments.

2.2 SOC changes under different fertilization schemes

Changes in SOC under different fertilization schemes are presented in Table 2. Annual change in SOC under particular fertilization schemes was in the order O, OF>NPK, N, NP for DCs, and O, OF>NPK>N, NP for RPs. Greatest annual increase was for organic amendments of O and OF treatments at 0.23 and 0.22 g kg^{-1} for DCs, and 0.28 and 0.30 g kg^{-1} for RPs. A lower increase occurred in the range 0.02–0.10 g kg^{-1} for DCs and 0.03–0.11 g kg^{-1} for RPs under chemical fertilization. However, there were much higher mean annual SOC increases of 0.10 and 0.11 g kg^{-1} for DCs and RPs under compound NPK chemical fertilization compared with N, NP and other unbalanced fertilizations, with increases of 0.02–0.07 g kg^{-1} and 0.03–0.04 g kg^{-1} for DCs and RPs, respectively. Here, the mean increase in SOC under organic amendments was almost double that under balanced chemical fertilization, which was already double that under unbalanced chemical fertilization. While the higher increase under organic amendments could be attributed to direct input of organic matter through manure and straw application, the increase in SOC under balanced fertilization could be accounted for by increased root input to soil as crop yield increased by improving nutrient supply [10,20]. By contrast, the small increase of 0.07–0.11 g kg^{-1} yr^{-1} under NP fertilization and the negligible increase of 0.02–0.04 g kg^{-1} yr^{-1} in SOC under other unbalanced fertilizations may be explained by decreased crop yield. Decrease in topsoil SOC may be also due to increased N availability, inducing increased microbial decomposition of SOC under

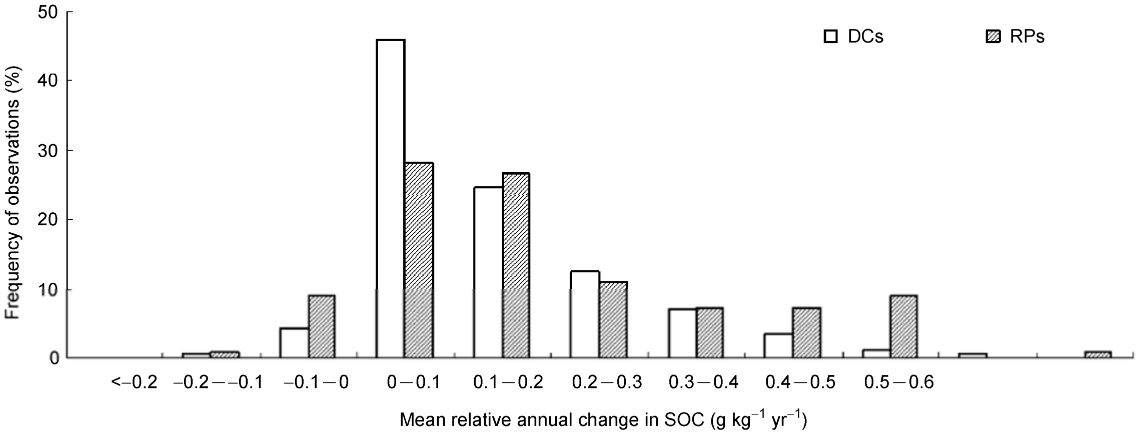

Figure 1 Frequency distribution of SOC changes in long-term experiments of dry croplands (DCs) and rice paddies (RPs).

Table 1 Distribution of soil organic carbon (SOC) dynamics and relative annual change (RAC) on different cropland types$^{a)}$

Cropland type	SOC change	Observations (n (%))	Mean RAC (g kg^{-1} yr^{-1})	Overall RAC (g kg^{-1} yr^{-1})	Experiment duration (yr)	Overall mean durations (yr)
DCs (n=346)	Increase	329 (95.1)	0.14±0.13	0.13±0.13b	14.46±5.31	14.42±5.27
	Decrease	17 (4.9)	−0.04±0.04		13.53±4.60	
RPs (n=135)	Increase	122 (90.5)	0.21±0.18	0.19±0.18a	14.63±4.22	14.39±4.24
	Decrease	13 (9.6)	−0.03±0.03		12.15±3.93	
Total (n=481)	Increase	451 (93.8)	0.16±0.14	0.15±0.15	14.51±5.03	14.41±5.00
	Decrease	30 (6.2)	−0.04±0.04		12.93±4.31	

a) Different lower case characters in the same column indicate significant difference between dry croplands (DCs) and rice paddies (RPs) at $P<0.05$.

Table 2 Relative annual change (RAC) in soil organic carbon (g kg^{-1}) and mean fertilizer application rate (kg ha^{-1}) under different fertilization treatments$^{a)}$

Cropland type		Fertilization treatment						
		N	NP	NPK	O	OF	Others	Whole/Mean
DCs (n=346)	Observations (n)	33	76	44	49	106	38	346
	Mean RAC	0.04±0.08bc	0.07±0.05b	0.10±0.09b	0.23±0.14a	0.22±0.13a	0.02±0.04c	0.13±0.13B
	Mean nutrient application	177.7±74.9	240.3±112.0	517.3±375.1	329.1±310.9	620.2±299.5	188.9±140.4	/
RPs (n=135)	Observations (n)	7	12	31	17	53	15	135
	Mean RAC	0.03±0.04c	0.04±0.04c	0.11±0.11b	0.28±0.20a	0.30±0.17a	0.03±0.08c	0.19±0.18A
	Mean nutrient application	191.8±96.9	329.7±168.1	497.1±198.8	826.9±828.0	741.5±515.1	248.1±188.6	/
Total (n=481)	Observations (n)	40	88	75	66	159	53	481
	Mean RAC	0.04±0.07b	0.06±0.05b	0.11±0.10b	0.24±0.16a	0.24±0.15a	0.03±0.05b	0.15±0.15
	Mean nutrient application	180.1±77.9	252.5±123.8	508.9±312.8	457.3±536.9	660.6±387.6	205.7±156.0	/

a) Different lower case characters in the same row indicate significant difference between fertilization treatments at $P<0.05$; different capital characters in the same column indicate significant difference between dry croplands (DCs) and rice paddies (RPs) at $P<0.05$. N, inorganic nitrogen fertilizer only; NP, compound inorganic nitrogen and phosphorus fertilizers; NPK, compound inorganic nitrogen, phosphorus and potassium fertilizers; O, organic fertilizers only; OF, combined inorganic fertilizers and organic amendments; Others, other unbalanced fertilizations (P, K, PK, NK).

the N-only treatment.

2.3 SOC changes under different fertilization and experiment duration

Experiment duration ranged from 6 to 25 years and varied across sites. Several blocks were designed for analyzing the effect of experiment duration on SOC changes. Calculated mean annual SOC changes according to the duration blocks are presented in Table 3. The RAC decreased with increasing experiment duration for dry croplands, but was not significant for rice paddies. Mean relative annual increase in SOC under fertilization in RPs showed no significant decline through the whole range of experimental durations, while that in DCs decreased when the experiment lasted >20 years. Relatively higher RAC values occurred in duration blocks of 6-15 years for DCs and 11–20 years for RPs. In a modeling study of soil monitoring data, Xu (2008) suggested that soil SOC sequestration could be effective for 34 years for DCs and 27 years for RPs [19]. While the experimental durations examined here were shorter than the suggested sequestration duration, a mean relative increase in SOC under the fertilization treatments at the experimental sites reached 0.07–0.16 g kg^{-1} yr^{-1} when the experiments lasted >20 years. This is much higher than that reported for soil monitoring sites by Pan *et al.* [4]. It seems that SOC sequestration could be effective for longer durations than the durations of conventional agro-management practices. Hence, soil SOC sequestration rate could be overestimated when using the rate assessed with data from shorter-term experiments.

The RAC changed under different fertilization schemes and with different experiment durations (Figure 2). For DCs, there were significant differences in RAC between different treatments of O and OF, NPK and unbalanced fertilizations, and over and fewer than 20 years. This may indicate that rational fertilization with compound chemical fertilizers and combined inorganic/organic fertilizers may have a stronger effect on SOC increase than the other schemes over 20 years. In contrast, the significant differences in SOC increases between fertilization schemes remain over 20 years in RPs. Annual SOC increase in RPs over 20 years under organic amendments was double that under compound chemical fertilization, which itself was double that under unbalanced fertilizations. Therefore, SOC sequestration in RPs under rational fertilizations may be feasible for over 20 years and may be sustained under optimum fertilization in the longer term. In a case study of an agro-ecosystem experiment on a rice-rapeseed rotation system from the Tai Lake region, China, Pan *et al.* [20] reported that rice yield

Table 3 Changes in mean relative annual change (RAC) (g kg^{-1} yr^{-1}) with blocks of monitoring duration[a)]

Cropland type		Experiment duration (yr)				
		6–10	11–15	16–20	21–25	Whole/mean
DCs (n=346)	Observations (n)	101	89	110	46	346
	Mean RAC	0.19±0.15a	0.15±0.14a	0.10±0.09ab	0.07±0.07b	0.13±0.13B
RPs (n=135)	Observations (n)	36	36	47	16	135
	Mean RAC	0.15±0.18a	0.20±0.18a	0.21±0.19a	0.16±0.14a	0.19±0.18A
Total (n=481)	Observations (n)	137	125	157	62	481
	Mean RAC	0.18±0.16a	0.16±0.16a	0.13±0.14ab	0.09±0.10b	0.15±0.15

a) Different lower case characters in the same row indicate significant difference between monitoring durations at $P<0.05$; Different capital characters in same column indicate significant difference between dry croplands (DCs) and rice paddies (RPs) at $P<0.05$.

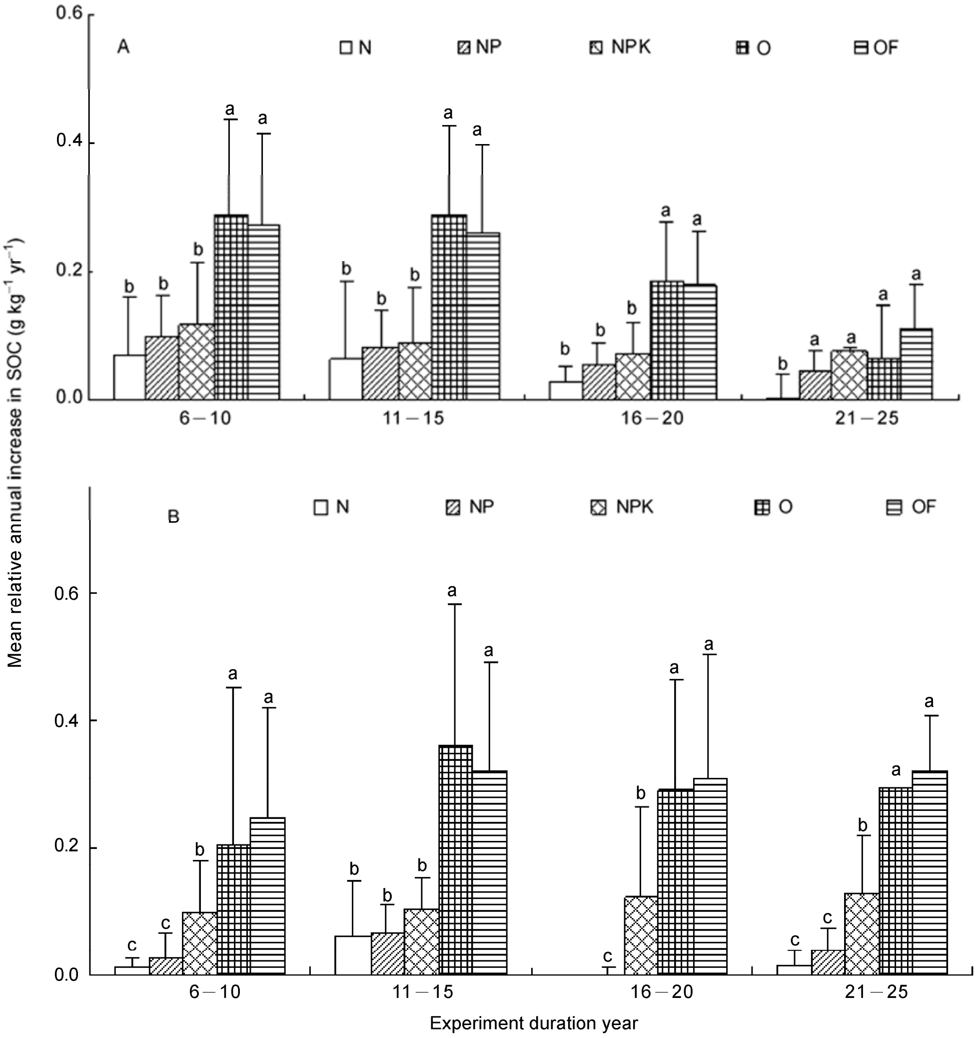

Figure 2 Changes in mean relative annual SOC increase with experiment durations for dry croplands (A) and rice paddies (B) under different fertilization treatments. Different lower case characters in the same group indicate significant difference between the fertilization treatments at $P<0.05$. N, inorganic nitrogen fertilizer only; NP, compound inorganic nitrogen and phosphorus fertilizers; NPK, compound inorganic nitrogen, phosphorus and potassium fertilizers; O, organic fertilizers only; OF, combined inorganic fertilizers and organic amendments; Others, other unbalanced fertilizations (P, K, PK, NK).

and SOC were significantly higher under combined inorganic/organic fertilization than chemical fertilization only, even when the experiment lasted >22 years. The findings here give further support for the double win-win effect of SOC accumulation on rice production and greenhouse gas mitigation in rice agriculture, and further demonstrate that rice agriculture has a high potential for C sequestration and productivity under rational fertilizations [4,7,8]. Thus, good management of RPs may offer options not only for enhancing China’s food production but also for climate change mitigation capacity in agriculture.

3 Conclusions

Through a data synthesis and meta-analysis of SOC changes under different fertilization schemes across China's croplands, we reached the following conclusions: (i) an overall trend of SOC increase has occurred at experimental sites, which was higher in RPs than DCs; (ii) there was a much higher SOC increase under balanced fertilization compared with unbalanced fertilizations in both DCs and RPs; and (iii) the higher increase in SOC under rational fertilization can be sustained in DCs for <20 years, but >20 years in RPs. These findings suggest that fertilization, as a crucial factor in agro-management practices,may exert a profound effect on SOC sequestration, especially in RPs. Rational fertilization design and extension would offer a strategy to enhance both C sequestration and cereals production in China's croplands .

This cross-site analysis allows an understanding of overall SOC changes under differing fertilization schemes using experimental data from across China. However, the processes and mechanisms behind SOC increase under the different fertilization schemes require further study.

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Appendix Table 1 Long-term agro-ecosystem fertilization experiments used in this study

Location	Soil type	Crop system	Duration	Fertilization treatment a)	Literature b)
Huaiyuan, Anhui	Lowland clay soil	Wheat-corn	1992–2000	I: CK, II: CF	[1]
Huangshan, Anhui	Paddy soil	Early-late rice	1987–1995	I:CK, II:CF, III:O, IV:OF	[2]
Mengcheng, Anhui	Black soil	Wheat-soybean	1995–2004	I:CK, II:CF	[3]
Tongcheng, Anhui	Paddy soil	Rice-rice-alfalfa	1990-1994	I:CK, II:CF, III:O, IV:OF	[4]
Quxi, Anhui	Black soil	Wheat-soybean	1981–1996	I:CK, II:CF, III:O, IV:OF	[5]
Changping, Beijing	Fluvo-aquic soil	Wheat-corn-corn	1984–2003	I:CK, II:CF, III:O, IV:OF	[5]
Changping, Beijing	Fluvo-aquic soil	Winter wheat-summer corn	1990–2004	I:CK, II:CF, IV: OF	[7]
Beibei, Chongqing	Paddy soil	Rice	1985–1995	I:CK, II:CF, IV:OF	[8]
Beibei, Chongqing	Paddy soil	Rice-wheat	1991-2002	I:CK, II:CF, III:O, IV:OF	[9]
Zhangye, Gansu	Irrigated Aaridisol	Wheat-corn	1982-1993	I:CK, II:CF, IV: OF	[10]
Dingxi, Gansu	Dark loessial soil	Wheat	1990–1999	I:CK, II:CF	[11]
Zhangye, Gansu	Irrigated desert soil	Spring wheat	1993–2003	I:CK, II:CF, III:O, IV:OF	[12]
Guangzhou, Guangdong	Paddy soil	Early-late rice	1983–1992	I:CK, II:CF, III:O, IV:OF	[13]
Zengcheng, Guangdong	Paddy soil	Early-late rice	1987–2003	I:CK, II:CF, IV:OF	[14]
Changli, Hebei	Cinnamon soil	Wheat-corn	1990–1998	I:CK, II:CF, IV:OF	[15]
Hengshui, Hebei	Fluvo-aquic soil	Wheat-corn	1979–2002	I:CK, II:CF, III:O	[16]
Hengshui, Hebei	Fluvo-aquic soil	Winter wheat-summer corn	1981–2004	II:CF, III:O, IV:OF	[17]
Xinji, Hebei	Fluvo-aquic soil	Winter wheat-summer corn	1980–1996	I:CK, II:CF, III:O, IV:OF	[18]
Wuji, Hebei	Fluvent	Wheat-corn	1986-1992	I:NF, II: CF	[19]
Zunhua, Hebei	Cinnamon soil	Wheat-corn	1995–2002	I:CK, II:CF, IV:OF	[20]
Fengqiu, Henan	Fluvo-aquic soil	Wheat-corn	1989–2005	I:CK, II:CF, III:O, IV:OF	[21]
Kaifeng, Henan	Fluvo-aquic soil	Wheat-corn	1988–1994	I:CK, II:CF, III:O, IV:OF	[22]
Runan, Henan	Calcic Inceptisol	Winter wheat-summer corn	1981–1997	I:CK, II:CF	[23]
Zhengzhou	Fluvent	Wheat-corn	1981-1990	I:CK,II:CF,,III: OF	[24]
Zhumadian, Henan	Fluvo-aquic soil	Peanut	1997–2003	I:CK, II:CF	[25]
Hailun, Heilongjiang	Black earth	Corn	1990–2004	I:CK, II:CF	[26]
Hailun, Heilongjiang	Black earth	Corn	1985–2004	I:CK, II:CF, III:O, IV:OF	[27]
Heihe, Heilongjiang	Dark-brown earth	Wheat(wheat/soybean)	1979–1994	I:CK, II:CF, III:O, IV:OF	[28]
Mishan, Heilongjiang	Albic soil	Wheat(wheat/soybean)	1987–2005	I:CK, II:CF, III:O	[29]
Mishan, Heilongjiang	Albic soil	Corn(wheat/soybean)	1987–2005	I:CK, II:CF, III:O	[29]
Tongcheng, Hubei	Paddy soil	Early-late rice	1981–2001	I:CK, II:CF, IV:OF	[30]
Wuhan, Hubei	Paddy soil	Rice-wheat	1981–2002	I:CK, II:CF, III:O, IV:OF	[31]
Hengyang, Hunan	Red earth	Corn-wheat	1990–2003	I:CK, II:CF, III:O, IV:OF	[32]
Ningxiang, Huanan	Paddy soil	Corn-rice	1986–2003	I:CK, II:CF, III:O, IV:OF	[33]
Qiyang, Hunan	Red earth	Wheat-corn	1990–2000	I:CK, II:CF, III:O, IV:OF	[34]
Taojiang, Hunan	Paddy soil	Corn-rice	1986–2003	I:CK, II:CF, III:O, IV:OF	[33]
Taoyuan, Hunan	Paddy soil	Rice-rice-green manure	1990–2004	I:CK, II:CF, III:O, IV:OF	[35]
Wugang, Hunan	Paddy soil	Early-late rice	1986–2005	I:CK, II:CF, III:O, IV:OF	[36]
Wugang, Hunan	Paddy soil	Rice-rice-green manure	1986–2003	I:CK, II:CF, III:O, IV:OF	[33]
Xinhua, Hunan	Paddy soil	Rice-rice-green manure	1986–2003	I:CK, II:CF, III:O, IV:OF	[33]
Zhuzhou, Hunan	Paddy soil	Rice-rice-green manure	1986–2003	I:CK, II:CF, III:O, IV:OF	[33]
Dehui, Jilin	Black earth	Corn	1999–2005	I:CK, II:CF, III:O, IV:OF	[37]
Gongzhuling, Jilin	Black earth	Corn	1980–1993	I:CK, II:CF, IV:OF	[38]
Meihekou, Jilin	Paddy soil	Rice	1983–1988	I:CK, II:CF, III:O, IV:OF	[39]
Changshu, Jiangsu	Paddy soil	Rice-wheat	1990–2001	I:CK, II:CF, IV:OF	[40]
Wujiang, Jiangsu	Paddy soil	Rice-rape	1987–2004	I:CK, II:CF, IV:OF	[41]

(*To be continued on the next page*)

(*Continued*)

Location	Soil type	Crop system	Duration	Fertilization treatment a)	Literature b)
Shuining, Jiangsu	Saltic Eentisol	Wheat-corn	1986-1993	I:CK,II:CF, III:O,IV: OF	[42]
Xuzhou, Jiangsu	Fluvo-aquic soil	Wheat-corn	1980–1999	I:CK, II:CF, III:O, IV:OF	[43]
Zhenjiang, Jiangsu	Alfisol	Early-late rice	1983–1997	I:CK, II:CF, IV:OF	[44]
Experimental site	Soil type	Crop system	Duration	Fertilization treatment	Literature
Jinxian, Jiangxi	Paddy soil	Early-late rice	1981–2003	I:CK, II:CF, IV:OF	[45]
Jinxian, Jiangxi	Red earth	Early-late rice-fallow	1986–1996	I:CK, II:CF, III:O, IV:OF	[18]
Yingtan, Jiangxi	Paddy soil	Early-late rice	1991–2004	I:CK, II:CF	[46]
Shenyang, Liaoning	Entic Molisol	Corn	1980-1990	II:CF,III:O,IV:OF	[47]
Fengcheng, Liaoning	Brown earth	Corn	1992–2006	I:CK, II:CF, III:O, IV:OF	[48]
Kazuo, Liaoning	Cinnamon soil	Cotton	1987–1998	I:CK, II:CF, III:O, IV:OF	[49]
Panjin, Liaoning	Paddy soil	Corn	1978–1985	I:CK, II:CF, III:O, IV:OF	[50]
Shenyang, Liaoning	Brown earth	Corn-soybean-corn	1979–2002	I:CK, II:CF, III:O, IV:OF	[51]
Shenyang, Liaoning	Brown earth	Corn	1987–1994	I:CK, II:CF, III:O, IV:OF	[52]
Wafangdian, Liaoning	Brown earth	Corn-soybean	1986–1995	I:CK, III:O	[53]
Wafangdian, Liaoning	Meadow soil	Corn-soybean	1988–1994	I:CK, III:O	[53]
Yucheng, Shandong	Fluvo-aquic soil	Winter wheat-summer corn	1986–2000	I:CK, II:CF, IV:OF	[54]
Hequ Shanxi	Cinnamon soil	Broomcorn millet-potato	1988–2005	I:CK, II:CF, III:O, IV:OF	[55]
Yangling, Shaanxi	Dark loessial soi	Wheat-corn	1980-1992	I:CK, II:CF, III:O, IV:OF	[56]
Changwu, Shannxi	Dark loessial soil	Wheat	1984–2005	I:CK, II:CF	[57]
Changwu, Shannxi	Dark loessial soil	Wheat	1984–2004	I:CK, II:CF, III:O, IV:OF	[57]
Changwu, Shannxi	Dark loessial soil	Winter wheat	1984–1999	I:CK, II:CF	[58]
Changwu, Shannxi	Dark loessial soil	Wheat-corn	1984–2000	I:CK, II:CF	[59]
Changwu, Shannxi	Dark loessial soil	Wheat-broomcorn millet	1984–1999	I:CK, II:CF, IV:OF	[59]
Changwu, Shannxi	Dark loessial soil	Wheat(wheat-peas/wheat-corn)	1984–2000	I:CK,II:CF,III:O,IV:OF	[60]
Changwu, Shannxi	Dark loessial soil	Winter wheat	1984–2004	I:CK, II:CF	[61]
Heyang, Shannxi	Cinnamon soil	Wheat	1990–2000	I:CK, II:CF, IV:OF	[62]
Yangling, Shannxi	Cinnamon soil	Wheat-corn	1977–2002	I:CK, II:CF, IV:OF	[63]
Yangling, Shannxi	Cinnamon soil	Winter wheat-summer corn	1990–2002	I:CK, II:CF, IV:OF	[64]
Yangling, Shannxi	Loess plagen soil	Wheat	1984–1990	I:CK, II:CF, III:O, IV:OF	[65]
Shanghai	Paddy soil	Wheat-rice-rice	1979–1993	I:CK, II:CF, III:O, IV:OF	[66]
Luzhou,Sichuan	Paddy soil	Wheat-rice-rice	1984-1993	I:CK, II:CF, III:O	[67]
Suining, Sichuan	Paddy soil	Rice	1985–1995	I:CK, II:CF, III:O, IV:OF	[8]
Wusheng, Sichan	Paddy soil	Rice	1983–1999	I:CK, II:CF, III:O, IV:OF	[68]
Xiqing, Tianjing	Fluvo-aquic soil	Winter wheat-summer corn	1979–2003	I:CK, II:CF, IV:OF	[69]
Fukang, Xinjiang	Grey desert soil	Wheat	1991–2004	I:CK, II:CF, IV:OF	[70]
Wulumuqi, Xinjiang	Grey desert soil	Corn-spring wheat-winter wheat	1990–2002	I:CK, II:CF, IV:OF	[71]
Chuxiong, Yunnan	Paddy soil	Rice-wheat	1987–1998	I:CK, II:CF, III:O, IV:OF	[72]
Fuyang, Zhejiang	Paddy soil	Rice-rice-wheat	1985-1994	I:CK, II:CF, III:O, IV:OF	[73]
Hangzhou, Zhejiang	Paddy soil	Wheat-rice-rice	1991–2002	I:CK, II:CF, III:O, IV:OF	[74]
Hangzhou, Zhejiang	Paddy soil	Wheat-rice-rice	1996–2006	I:CK, II:CF, III:O, IV:OF	[75]
Quzhou, Zhejiang	Paddy soil	Wheat(rape)-rice-rice	1992–1997	I:CK, II:CF, IV:OF	[76]
Quzhou, Zhejiang	Paddy soil	Wheat-rice-rice	1988–1997	I:CK, II:CF, IV:OF	[76]
Quzhou, Zhejiang	Paddy soil	Wheat-rice-rice	1983–1997	I:CK, II:CF, IV:OF	[76]

a) CK, no fertilizer; CF, single or compound inorganic fertilizers of N, P and K fertilizer; III: O, organic fertilizers only (including rice/wheat/corn straw, milk vetch, farmyard/pig/cow/chook/green manure) and IV: OF, the combined of inorganic fertilizers with organic amendments. b) Data source (in an order as appeared in the table)

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