Long-term effects of fertilizer managements on crop yields and organic carbon storage of a typical rice–wheat agroecosystem of China

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Abstract The present paper summarizes the results from a long-term experiment setup in 1980 in the Taihu Lake region, China, to address the yield sustainability, the dynamic changes of soil organic carbon (SOC) storage, and soil fertility in the rice–wheat ecosystem. Treatments in three replicates comprising manure-treated and chemical fertilizer-treated groups (two factors), each having seven sub-treatments of different combinations of inorganic nitrogen (N), phosphorus (P), potassium (K), and rice straw, were randomly distributed. Results showed that the treatments of manure (pig manure from 1980 to 1996 and oil rape cake thereafter) + N + P + K (MNPK) and chemical fertilizer + N + P + K (CNPK) produced the highest and the most stable yields for both rice and wheat within the respective fertilizer treatment group. Potassium fertilization was necessary for yield sustainability in the ecosystem. Treatments of straw (as rice straw) + N (CRN) and manure + straw + N (MRN) produced more stable yield of rice but less stable of wheat. It was therefore recommended that straw should be only incorporated during the rice season. SOC contents in all treatments showed increasing trends over the period, even in the control treatment. Predicted SOC in chemical fertilizer-treated plots (mostly yet attainable) ranged from 16 to 18 g C kg^{-1}, indicating the high carbon (C) sequestration potential of the soil as compared to the initial SOC. SOC in manure- or straw-treated plots ranged from 17 to 19 g C kg^{-1}, which had been attained roughly 10 years after the experiment was initiated. Nutrient balance sheet showed that there was P surplus in all P-treated plots and a steady increase in Olsen-P over a 24-year period in 0–15 cm soil, which contributed little to crop yield increases. It was therefore suggested that P fertilization rate should be decreased to 30–40 kg P ha^{-1} year^{-1}. Comparison of yields among the treatments showed that wheat was more responsive to P fertilizer than rice. Thus P fertilizer should be preferably applied to wheat. Soil pH decrease was significant over the 24-year period and was not correlated with fertilizer treatments. The overall recommendation is to incorporate straw at 4,500 kg ha^{-1} year^{-1} during the rice season only, with additional 190 kg N ha^{-1} year^{-1}, 30–40 kg P ha^{-1} year^{-1} mainly during the rice season, and 150–160 kg K ha^{-1} year^{-1}. Further research on the unusual P supply capacity of the soil is needed.

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Introduction

Rice–wheat ecosystem is the largest rice-based sub-ecosystem (12 million ha in China), accounting for roughly half of the total rice growth land in China (Timsina and Connor 2001). The Taihu Lake region, covering 36,900 km^2 in total area with 1.6 million ha of arable land, has been known as

one of the oldest rice-growing areas in China (and probably in the world too), with at least 1,500 years of rice-growing history by literature record (Ellis and Wang 1997) and about 6,000 years by carbon dating and archaeological studies (Cao et al. 2006). Throughout such a long rice-growing history, the soil fertility was maintained basically by applying farmyard manure, river mud (especially in the Taihu Lake region), and legume plant materials. Straw was typically removed for cooking fuel but the remaining ashes were meticulously collected and returned to soils (Ellis and Wang 1997). These materials supply the nutrients for crop growth on one hand and maintain or increase the levels of soil organic matter (SOM) on the other hand. Under such nutrient managements, soils in the Taihu Lake region have been kept fertile and productive for many years. Consequently, the region has been widely known as a "rice granary" or a "fish and rice village" in China. The traditional nutrient management systems had no substantial change until the 1970s when chemical fertilizers (principally N fertilizer) have been increasingly in use, and the traditional nutrient sources have been gradually replaced. While this fertilizer management shift brought about remarkable grain yield increase, the long-term sustainability of the rice-based ecosystem and judicious use of fertilizers became concerns. Without exogenous carbon-rich material inputs, soils might undergo SOM loss, which has been considered essential for long-term sustainability (Jenkinson 1991; Nel et al. 1996; Aref and Wander 1998) and productivity (Ladha et al. 2003a; Yadvinder-Singh et al. 2004). With these backgrounds, a long-term experiment was set up in 1980 in the Taihu Lake region, to assess the impact of modern fertilizers on soil fertility and sustainability of the historically rice-growing soil.

Recent environmental issues put additional values to the long-term experiment. The fact that the Taihu Lake water body has been undergoing accelerated eutrophication for two decades becomes a serious concern. Reports indicated that significant quantities of phosphorus (P) (Zhang et al. 2003a, b; Shan et al. 2005) and nitrogen (N; Tian et al. personal communication) could be lost from the rice–wheat ecosystem in the area via runoff, leaching, and drainage. The lost nutrients can be easily transported into the lake water body through the densely netted water channels (a featured landscape of this region) and therefore, have been considered as the potential nonpoint pollution sources to the water eutrophication. Soil P is particularly concerned because P fertilizer (together with N fertilizer) has been continuously applied for at least three decades in the region. Judicious use of fertilizers is therefore important in this region as far as the lake water eutrophication is concerned. The other issue is about the carbon (C) sequestration potential of paddy soils in China. Several recent reports showed that China's rice-based soils contain generally

higher soil organic carbon (SOC) than upland crop-based soils (Cai 1996; Erda et al. 1997; Pan et al. 2003; Wu et al. 2003; Song et al. 2005). The estimated easily attainable SOC sequestration potential by rice-based soils was 0.7 Pg and the maximum potential was 3.0 Pg (Pan et al. 2003). However, the data were calculated basically from the second State Soil Survey, which was completed in the 1980s. Approximately 25 years have elapsed, and there is little information available on the changes of SOC during this 25-year period, particularly on long-term controlled experiments. This data are of critical importance for accurate estimations of C sequestration potential (Lal 2004a) under present conditions and for elucidating the role of China agriculture in global climatic change.

Based on the above considerations, the results from the long-term experiment were summarized in this present paper, with emphasis on effects of fertilizer managements on crop yields, dynamics changes of SOC storage, and soil fertility in the rice–wheat agroecosystem. Recommended fertilizer rates were also proposed based on the long-term data.

Materials and methods

Study site and soil

The experiment site is located at Suzhou (31°32′45″N; 120°41′57″E), Jiangsu Province, China. The region receives annually 3,039 sunshine hours and 1,128 mm of rainfall. Average annual temperature is 15.7°C. Effective accumulated temperature (>10°C) is 4,947°C. The soil, derived from loessal deposits, is clay loam in texture with hydromica and semectite as the dominating clay minerals, and it is classified as Typ-Fel-Stagnic Anthrosols according to the Chinese soil classification system (Shi et al. 2004). This type of soil is a representative soil, accounting for 70% of total paddy soils in the Taihu Lake region. The soil (0–15 cm) sampled in 1980 contained 2.42% organic matter, 0.143% total N, 428 mg kg^{-1} total P, 8.4 mg kg^{-1} NaHCO$_3$-extractable P (Olsen-P), 85 mg kg^{-1} ammonium acetate extractable K (NH$_4$Ac-K) and 237 mg kg^{-1} 1 mol HNO$_3$ extractable K (HNO$_3$-K), with an initial pH (H$_2$O) of 6.8.

Fertilizer treatments

The experiment was established in 1980. Treatments were arranged in a two-factor block randomization design with three replicates (Table 1). Each plot, 5×4 m in size, is separated by cement plates, which are 15 cm above soil surface so as to avoid water mixing among the plots. Irrigation and drainage are separated by different ditches.

Table 1 Description of nutrient inputs into different plots under rice–wheat rotations from 1980 to 2004[a]

Factor 1 Chemical fertilizer group		Factor 2 manure group	
Code	Treatment	Code	Treatment
C0	Control, no fertilizer	M0	Manure at the averaged rate equivalent to 103.1 kg N ha^{-1} yr^{-1}, 82.7 kg P ha^{-1} yr^{-1} and 70.1 kg K ha^{-1} yr^{-1}
CN	150–300 kg N ha^{-1} yr^{-1} (depending years)	MN	Manure + CN
CNP	150–300 kg N ha^{-1} yr^{-1}+55.8 kg P ha^{-1} yr^{-1}	MNP	Manure + CNP
CNK	150–300 kg N ha^{-1} yr^{-1}+137.5 kg K ha^{-1} yr^{-1}	MNK	Manure + CNK
CPK	55.8 kg P ha^{-1} yr^{-1}+137.5 kg K ha^{-1} yr^{-1}	MPK	Manure + CPK
CNPK	150–300 kg N ha^{-1} yr^{-1}+55.8 kg P ha^{-1} yr^{-1}+137.5 kg K ha^{-1} yr^{-1}	MNPK	Manure + CNPK
CRN	150–300 kg N ha^{-1} yr^{-1}+~4500 kg rice straw ha^{-1} yr^{-1} equivalent to 40.6 kg N ha^{-1} yr^{-1}, 5.5 kg P ha^{-1} yr^{-1} and 59.8 kg K ha^{-1} yr^{-1}	MRN	Manure + CRN

[a] Variations of N, P, K application rates were given in "Materials and Methods."

Treatments shown in Table 1 were designed according to common local practices during the 1980s. CNPK treatment reflected the fertilization rates recommended during the 1980s based on the short-term experiment results. Annual fertilization rates were nearly equally allocated to wheat and rice. Urea, calcium superphosphate, and KCl (before 1995) or K_2SO_4 (1995–present) are used as N, P, and K fertilizers, respectively. Pig manure from 1980 to 1996 and oil rape cake (powder) thereafter are applied as manure at the rates calculated on the basis of total N input equal to pig manure. Manure and calcium superphosphate are all applied basally. Rice straw (in relevant treatments) was cut into fragments 10–15 cm in length, incorporated into the soil by plowing immediately after wheat harvest or mulched at soil surface after rice harvest. Wheat straw was removed from the plots and not used for incorporation because it showed adverse effects on seedling growth of succeeding rice by short-term experiments conducted in the early 1980s on the same soil. KCl or K_2SO_4 are basal applied in half, leaving another half to be top-dressed at the fast vegetative-growing (tillering) stage. Half of urea is basal applied and another half top dressed by splitting into 2–3 portions and applied at different growing stages according to crop demand.

Nutrient contents of organic materials (pig manure, oil rape cake, and straw) were actually measured before being applied during each season. Based on the measured N contents, the application rate of pig manure and oil rape cake in terms of dry weight was calculated each year so as to achieve N input rate at approximately 90 kg N ha^{-1} $year^{-1}$. Variation of actual N input derived from pig manure and oil rape cake ranged from 85.7 to 122.1 kg N ha^{-1} $year^{-1}$ (extremes), with a mean value of 103.1 kg N ha^{-1} $year^{-1}$ averaged over the 24-yaer period (Table 1). Corresponding variation of actual P input ranged from 77.3 to 90.8 kg P ha^{-1} $year^{-1}$, with a mean value of 82.7 kg

P ha^{-1} $year^{-1}$; actual K input ranged from 54.4 to 88.6 kg K ha^{-1} $year^{-1}$, with a mean value of 70.1 kg K ha^{-1} $year^{-1}$. For straw amendment, the application rate in terms of dry weight was fixed. Variation of actual N input derived from straw materials, calculated on the basis of actually measured nutrient contents, ranged from 33.2 to 45.7 kg N ha^{-1} $year^{-1}$, with a mean value of 40.6 kg N ha^{-1} $year^{-1}$ averaged over the 24-year period. Corresponding variation of actual P input derived from straw ranged from 3.1 to 6.5 kg P ha^{-1} $year^{-1}$, with a mean value of 5.5 kg P ha^{-1} $year^{-1}$; the variation of K input ranged from 42.8 to 70.4 kg K ha^{-1} $year^{-1}$, with a mean value of 59.8 kg K ha^{-1} $year^{-1}$.

The target N input rates derived from chemical fertilizers varied with years ranging from 150 to 225 kg N ha^{-1} $year^{-1}$ between 1980 and 1989 and 300 kg N ha^{-1} $year^{-1}$ between 1990 and 2004. The target N fertilization rates were changed basically in accordance with the changes of cropping systems (specified in "Cropping System" section below). However, the target P and K rates were fixed all over the experimental period. Once the target rates were set, application rates in terms of dry weight were calculated according to the nutrient contents, which were actually measured on the samples from each batch of purchase.

Cropping system

The cropping system is basically one crop of rice (*Oryza sativa*) and one crop of winter wheat (*Triticum aestivum*) per year, except the year of 1981 when two crops of rice were grown, the years of 1982 and 1984 when naked barley (*Hordeum vulgare* var. nudum) instead of wheat was grown, the years of 1994 and 1995 when oil rape (*Brassica chinensis)* instead of wheat was grown, and the year of 2000 when broad bean (*Vicia faba*) instead of wheat was grown. Wheat was seeded onto the soil surface roughly 10 days before rice harvest (a practice called "zero-tillage

direct seeding" commonly adopted by local farmers) in October and was harvested in May. Rice was transplanted at the age of 4.5–5 leaves in early June. Soils are usually water submerged most of the time during the rice-growing season (from early June to early October), with 2–3 periods of alternative wetting and drying, each period lasting for 3–5 days.

Rice cultivars used were as follows: Kunnongxuan in 1981, Yuanfenzao in 1982, Suyugen #7 in 1983, Zaodan #8 from 1984 to 1989, Yayiu #2 from 1990 to 1996, Suxianggen #1 from 1997 to 1998, and Wuyungen #7 from 1999 to 2004. Wheat cultivars Sumai #4 was used from 1980 to 1998 and Su-9356 from 1999 to 2004. These cultivars were selected from the cultivar lists recommended by the Crop Variety Approval Committee of Jiangsu Province (CVACJP). The cultivar selections were made on the basis of similar yield potentials tested and issued by CVACJP so as to keep the yield potentials as consistently as possible. Cultivar changes were inevitable because of variety degeneration.

Sampling and analysis

Upon harvest, crops were cut roughly 2 cm above the soil surface, and the above-ground biomass was completely removed. All remained that in the soil was regarded as "roots." Grain seeds were harvested with threshold machine, sun-dried to ~14% water content (oven-dry basis), and weighted as the yields.

Soils from the top 15 cm in different plots were sampled at the harvest of rice, air dried, sieved through a 2-mm screen, and stored in plastic bottles for later analysis. Soil chemical properties were analyzed on all stored samples in 2004. Grain seeds, straw, and manure samples were processed similarly but analyzed each year. Crop root samples were collected manually by pulling them out from each plot, washed with tap water, oven dried, stored, and analyzed in the year of sampling.

To calculate C input into soils, it was assumed that crop roots that remained in the soil after harvest were the only crop-derived C sources, excluding metabolites excreted during crop growth. To estimate the amount of roots that remained in the soil, three sites of nearby farmers' fields were chosen on the basis of N fertilizer rates and the crop yields that were similar to those of corresponding plots. Soils $30 \times 30 \times 60$ cm from the nearby farmers' fields were dug out and carefully washed with tap water. All the roots from the soil were collected, oven dried, and weighted. Crop yield of the same field was recorded so as to calculate the ratio of yield/roots. Because of its destructive nature, the root weight measurements had to be conducted on the nearby farmers' fields, not within the plots. The ratios obtained as such were compared with the values reported in literatures under the same or similar soil and cropping conditions. The averaged yield/root ratios over the actually measured and reported values were 0.4 for wheat and 0.3 for rice, which were taken to estimate the quantity of roots that remained in the soil. C, N, P, and K in roots sampled as such were also measured, which were averaged with the hand-pulled samples.

Straw, grain, and manure samples were digested in a tri-acid mixture (HNO_3:$HClO_4$:H_2SO_4 at a 3:1:1 ratio) and analyzed for K by atomic absorption spectrophotometer and P by colorimeter (Yoshida et al. 1976). Subsamples were digested in concentrated H_2SO_4 and analyzed for N by micro-Kjeldahl distillation (Bremner 1996). Organic C contents of plant materials, manure, and soils were measured by wet combustion method (Nelson and Sommers 1996). Soil total N was measured by micro-Kjeldahl distillation method (Bremner 1996) and soil available N by the method described by Cornfield (1960) and modified by Wang et al. (2001). Soil Olsen-P was extracted with $NaHCO_3$ (Olsen et al. 1954). Soil available K was extracted with 1 M of ammonium acetate (NH_4OAc-K).

Data processes

Analysis of variance and multiple comparisons in SPSS software package (v 13) were used to process the data. The analysis model was chosen according to the field experiment design (two-factor block randomization design). Data-fitting processes were performed with Sigma Plot 9 by choosing different equations based on converges. For the trends of crop yields and soil nutrient contents over the years, linear regression equation was chosen. The equation of exponential raise to maximum (binomial with four parameters in) was used to simulate the soil C changes.

The quantitative assessment of the sustainability of the agricultural practice developed by Singh et al. (1990) was adopted to study the comparative performance of different fertilizer treatments. The sustainable yield index (SYI) of a given treatment was calculated as follows: $SYI = (\overline{Y} - Sd)/Y_{max}$, where $\overline{Y}$ is the average yield across years; Sd is the standard deviation and Y_{max} is the maximum yield observed over years in the treatment. The SYI can be any value from 0 to 1. When Sd is high, the value of SYI will be closer to 0, indicating the unstable nature of yielding in the treatment.

Results

Crop yields

The averaged yields of rice and wheat over 24 years among all treatments were summarized in Table 2. MNPK

Table 2 Summary of crop yields and yield sustainability indexes of different treatments

Treatment		Rice				Wheat			
		$\overline{Y}$[a]	Y_{max}[b]	Sd[c]	SYI[d]	$\overline{Y}$[a]	Y_{max}[b]	Sd[c]	SYI[d]
Manure treatment group	M0	5.7 e	8.2	0.96	0.58	2.9 f	4.7	0.82	0.46
	MN	6.5 c	9.1	1.16	0.58	3.5 d	5.8	1.15	0.40
	MNP	6.5 c	9.4	1.27	0.56	3.4 d	5.9	1.26	0.37
	MNK	6.6 b	9.4	1.26	0.58	3.9 b	5.9	1.03	0.48
	MPK	6.1 d	8.7	1.00	0.58	3.1 e	4.9	0.80	0.48
	MNPK	6.8 a	8.9	1.35	0.60	4.0 a	6.0	1.06	0.49
	MRN	6.7 b	9.1	1.19	0.60	3.7 c	5.9	1.05	0.46
Chemical fertilizer treatment group	C0	5.0 f	7.2	0.94	0.56	2.2 e	3.7	0.71	0.42
	CN	6.3 d	8.8	1.20	0.58	3.0 c	5.0	0.90	0.42
	CNP	6.4 bc	9.5	1.28	0.54	3.4 b	5.8	0.96	0.42
	CNK	6.3 cd	9.2	1.20	0.55	3.4 b	5.2	0.96	0.46
	CPK	5.3 e	8.3	1.04	0.52	2.5 d	4.4	0.71	0.41
	CNPK	6.6 a	9.2	1.22	0.59	3.7 a	5.6	0.93	0.50
	CRN	6.4 b	8.7	1.14	0.61	3.4 b	5.8	1.06	0.39

[a] $\overline{Y}$ stands for averaged yield. The different letters in lowercase after the number stand for significant differences at $p \le 0.05$ within each fertilizer treatment group by ANOVA.
[b] Y_{max} stands for maximum yield observed over the 24-year period in the experiments.
[c] Sd stands for standard deviation of yields over the 24-year period in the experiments.
[d] SYI stands for sustainable yield index for a given treatment calculated as $SYI = (\overline{Y} - Sd)/Y_{max}$.

supported 6.8 t ha^{-1} of rice and 4.0 t ha^{-1} of wheat, both being the highest yields among all the treatments. The control treatment (C0) supported 5.0 t ha^{-1} of rice yield and 2.2 t ha^{-1} of wheat yield, being 74 and 55% of the averaged highest yields of respective crops among the treatments. Manure-treated plots produced consistently 2–5% more yield of rice (depending on treatments) and 6–14% more yield of wheat than the chemical fertilizer-treated plots (excluding the treatments of CO, MO, CPK, and MPK). Within manure-treated group, MRN treatment produced the second highest rice yield (6.7 t ha^{-1}), being slightly but significantly lower than the highest rice yield in MNPK treatment (6.8 t ha^{-1}). MNK produced the second highest

wheat yield (3.9 t ha^{-1}) within manure-treated group, which was also slightly but significantly lower than the highest wheat yield in MNPK (4.0 t ha^{-1}). Similar trend held true in the chemical fertilizer-treated group.

In terms of yield sustainability, SYIs were consistently higher for rice than those for wheat. Both CRN and MRN (also MNPK) showed similarly higher SYI for rice than all the other treatments and both CNPK and MNPK showed similarly higher SYI for wheat (Table 2). There were no general trend of SYIs for rice and wheat between manure- and chemical fertilizer-treated plots.

Yield trends of most treatments (except CPK and MPK) over the 24-year period were presented in Figs. 1 and 2.

Fig. 1 Changes of wheat and rice yields over the 24-year period in chemical fertilizer-treated group
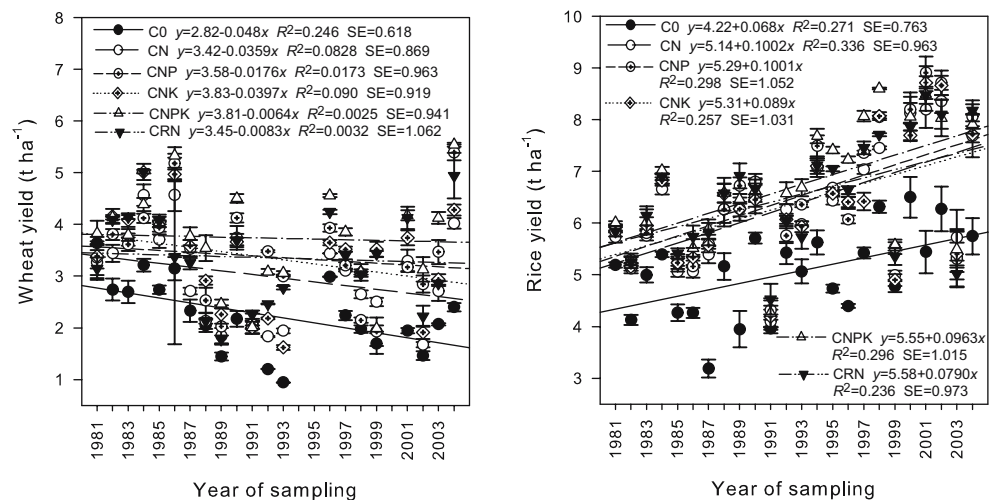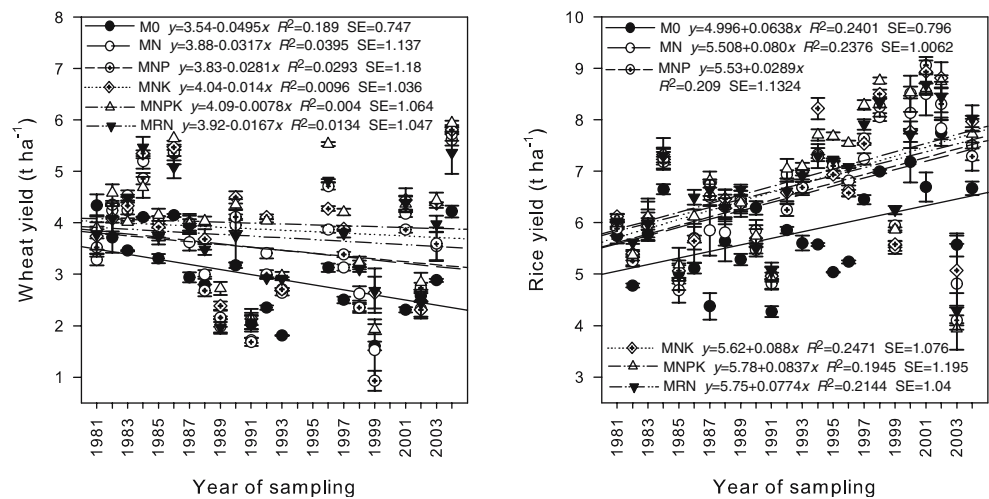
Fig. 2 Changes of wheat and rice yields over the 24-year period in manure-treated group

Rice yields showed increasing trend in all the treatments at the rate 0.029–0.1 t ha^{-1} year^{-1}, irrespective to fertilizer applications. However, the trend of wheat yield was generally declining, at the various rates depending on treatments. CNPK and MNPK showed marginal declining rates at 0.006–0.0078 t ha^{-1} year^{-1}, but other treatments showed more obvious declining trends at 0.008–0.05 t ha^{-1} year^{-1}. Nitrogen fertilizer brought about significant yield increase for both rice and wheat. However, P and K fertilizers brought about less yield increase in rice than that of wheat (Figs. 1, 2 and Table 2). The CN treatment, for example, produced the same or slightly lower rice yield but 11.8% lower wheat yield than CNP and CNK treatments (Table 2). A similar trend could be found among other corresponding treatments. The CN and MN treatments produced 93–96% of the highest rice yield (6.8 t ha^{-1}) and 75–88% of the highest wheat yield (4 t ha^{-1}).

Dynamic changes of SOC

SOC contents in all treatments showed increasing trends, even in the control treatment (Fig. 3). The simulated C accumulation equations shown in Fig. 3 allowed prediction of SOC changes by assuming the time approaches infinite. The predicted SOC listed in Table 3 was positively correlated to C input. SOC in manure- or straw-treated plots reached maximum levels in roughly 10 years after the experiment was established, but those in the chemical fertilizer-treated plots were still increasing (Fig. 3). By the year of 2004, SOC in almost all treatments arrived at their maximal levels. The predicted SOC in manure-treated plots showed consistently higher C accumulation than chemical fertilizer-treated plots, with averaged SOC being 17.8 g C kg^{-1} in manure-treated plots and 16.7 g C kg^{-1} in chemical fertilizer-treated plots (Table 3). Potassium-treated plots

showed consistently lower SOC accumulation than non-K treated plots. The SOC in CNPK treatment, for example, was 1.0 g C kg^{-1} lower than that in CNP treatment. The predicted SOC averaged over all K-treated plots was 16.9 g C kg^{-1} while non-K-treated plots was 17.5 g C kg^{-1} (Table 3).

Changes of soil total N, Olsen-P, and NH$_4$OAc-K

Changes of soil total N, Olsen-P, and NH$_4$OAc-K were shown in Table 4. Soil total N of all treatments including the control (C0) showed increasing trend over the time period (Fig. 4). The increase rates were roughly 0.01–0.02 g N kg^{-1} year^{-1}. Manure-treated plots maintained higher levels of total N than the chemical fertilizer-treated plots.

The trend of soil Olsen-P contents was significantly increased over the time in P-treated plots (MNP, MNPK, CNP, and CNPK; Fig. 5). By 2004, Olsen-P in MNP and MNPK treatments reached about 70 mg P kg^{-1} and CNP and CNPK treatments about 28 mg P kg^{-1}, with the increase rate about 2.9 and 0.8 mg P kg^{-1} year^{-1}, respectively. Olsen-P in MN treatment was also increased over time, but the level in 2004 was about 30 mg P kg^{-1} only (Fig. 5a). Olsen-P in MNK treatment showed an increase trend in the first 10 years and then decreased to 12 mg P g k^{-1} by 2004, which is still higher than the original level (8.4 mg P kg^{-1}). In the chemical fertilizer-treated group, Olsen-P was continuously increasing in P-treated plots but decreasing in the non-P-treated plots (Fig. 5b). Olsen-P in non-P-treated plots decreased to very low levels (2–3 mg P kg^{-1}) within 10 years after the experiment was initiated (Fig. 5b).

Soil NH$_4$OAc-K in all treatments showed a declining trend over the time period, even in K-fertilized treatments (Fig. 6). The decline rates were roughly 0.2–1.0 mg K kg^{-1}

Fig. 3 Dynamic changes of soil organic carbon contents in different treatments (0–15 cm)
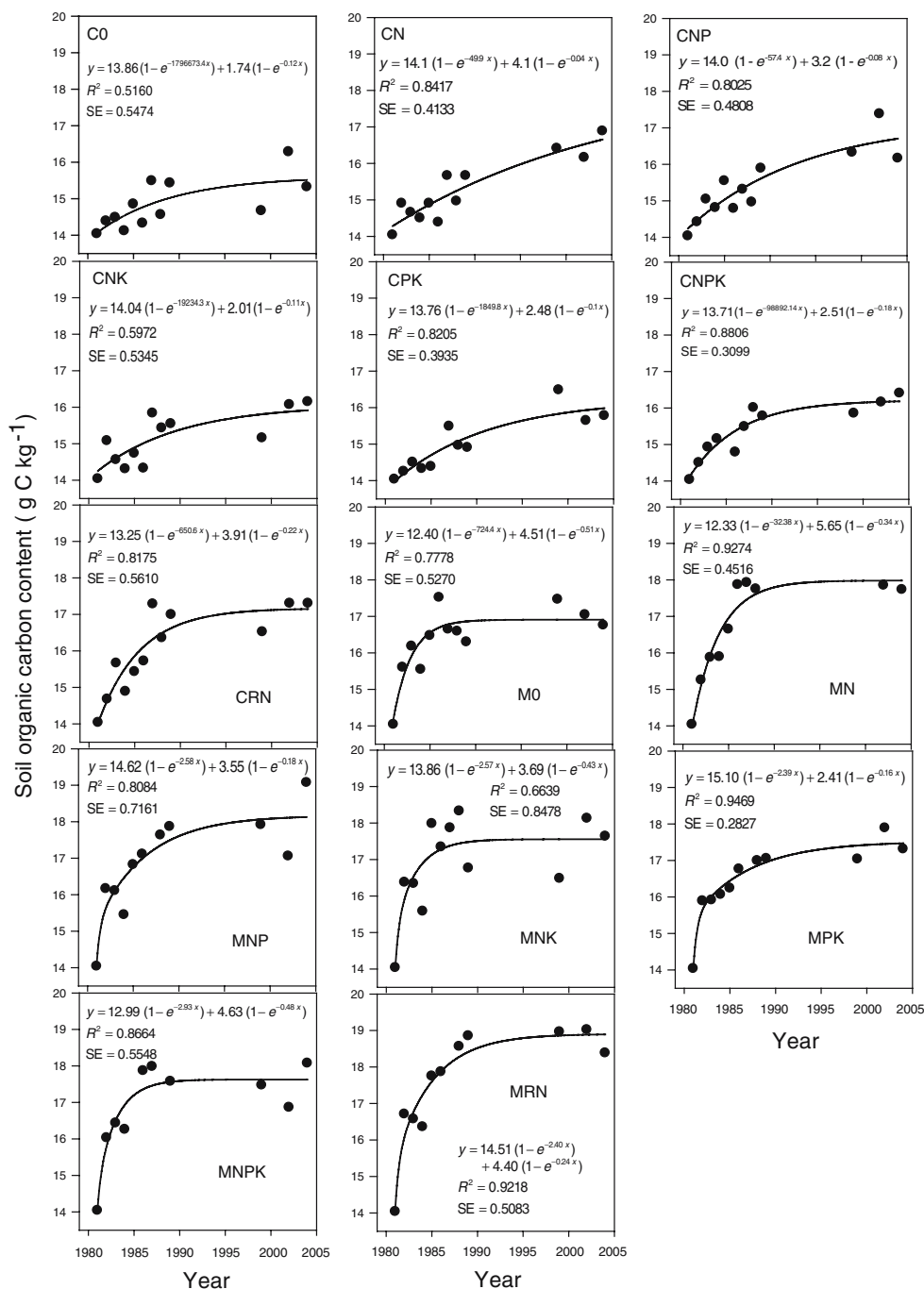
year^{-1} depending on treatments. Both CNPK and MNPK treatments maintained higher levels of NH$_4$OAc-K than the other treatments.

Nutrient balance and nutrient use efficiencies

Nutrient balance sheet (Table 5) showed that there was substantial N surplus in all N-treated plots. There was more N surplus in all N-treated plots in manure treatment group than those in chemical fertilizer treatment group. Higher

level of P surplus was found in all manure-treated plots than the level in chemically P-treated plots. The lowest P surplus occurred in CNPK treatment (13.3 kg P ha^{-1} year^{-1}). Both CNK and CNPK treatments showed K deficits while MNK and MNPK treatments showed slight K surpluses.

Taking C0 as the control for both chemical-fertilized and manure-fertilized treatments, apparent use efficiencies (AUE) of nutrients calculated were shown in Table 5. For AUE of N, manure-treated plots gave similar values as to

Table 3 Summary of C input and predicted SOC contents

Treatments	C input (kg C ha^{-1} yr^{-1})				Sum of C input (kg C ha^{-1} yr^{-1})	Predicted soil C[a] (g C kg^{-1})
	Rice residues	Wheat residues	Straw incorporated	Manure		
M0	596.7	361.0		1359.7	2317.5	16.9
MN	672.7	428.6		1359.7	2461.2	18.0
MNP	679.2	420.9		1359.7	2460.0	18.2
MNK	692.3	473.9		1359.7	2526.0	17.5
MPK	635.2	384.4		1359.7	2379.5	17.5
MNPK	704.8	488.3		1359.7	2552.9	17.6
MRN	692.2	456.2	1874.5	1359.7	4382.8	18.9
C0	518.7	274.6			793.3	15.6
CN	649.8	366.9			1016.8	18.2
CNP	666.1	413.1			1079.3	17.2
CNK	656.4	411.1			1067.5	16.1
CPK	553.7	303.7			857.5	16.2
CNPK	690.0	457.4			1147.4	16.2
CRN	668.8	410.8	1874.5		2954.2	17.2

[a] Calculated by assuming the time approaches infinite according to the simulated SOC accumulation patterns shown in Fig. 3

the chemical fertilizer-treated plots (MN vs CN, MNP vs CNP, MNK vs CNK, MNPK vs CNPK, and MRN vs CRN). The same trend held true for K use efficiencies (MNK vs CNK, MNPK vs CNPK, and MRN vs CRN). However, AUE of P in manure-treated plots was significantly lower than those in chemical fertilizer-treated plots (MNP vs CNP and MNPK vs CNPK). Manure-treated plots gave consistently lower N and P use efficiencies than chemical fertilizer-treated plots, as indicated by the grain yield increment per unit of nutrient applied (Table 5), which were calculated by comparison between yields of relative

treatments. However, opposite was true for K use efficiencies, which were higher in manure-treated plots than those in chemical fertilizer-treated plots (Table 5).

Discussion

Data presented in this paper showed that long-term use of chemical fertilizers did not adversely affect soil fertility and sustainability provided that N, P, and K fertilizers were judiciously used. Evidences supporting this generalization

Table 4 Selected soil fertility indexes of initial values in 1980 and of the values in 2004[a]

Treatment	Total N (g kg^{-1})	Available N (g kg^{-1})	Total P (g kg^{-1})	Olsen-P (mg kg^{-1})	NH$_4$OAc-K (mg kg^{-1})	HNO$_3$-K (g kg^{-1})	pH
Initial	1.43 d	NA[b]	0.428d	8.4e	85.0b	0.237cd	6.8a
M0	1.853ab	0.244a	0.675cd	34.2cd	56.4de	0.262b	6.0b
MN	1.928a	0.251 a	0.702c	31.7cd	61.5d	0.257bc	5.7b
MNP	1.886ab	0.247a	1.090b	77.3b	53.6e	0.297ab	5.8b
MNK	1.952a	0.239ab	0.655cd	26.2d	87.5b	0.263b	6.0b
MPK	1.923a	0.238ab	1.283a	96.0a	79.5bc	0.247c	5.9b
MNPK	1.814b	0.237b	1.048b	73.9b	63.5d	0.255bc	5.9b
MRN	1.915a	0.237b	0.655cd	26.9d	71.5cd	0.223d	5.7b
C0	1.582c	0.218c	0.400d	2.9e	57.6de	0.260b	6.1ab
CN	1.555c	0.221bc	0.404d	2.5e	55.6de	0.238cd	5.8b
CNP	1.782bc	0.251a	0.708c	28.8d	51.6e	0.259bc	6.0b
CNK	1.670 c	0.207c	0.368d	2.4e	75.5c	0.307ab	5.8b
CPK	1.597 c	0.213c	0.785c	40.9c	105.0a	0.285ab	5.9b
CNPK	1.576 c	0.174d	0.690cd	29.7d	77.5c	0.329a	5.7b
CRN	1.806 b	0.232b	0.380d	5.3e	59.5d	0.235cd	5.7b

[a] Means followed by the same letter in a column did not differ significantly ($P \le 0.05$) by Duncan's test.
[b] Initial data was not available.

Fig. 4 Trend of total N in soils of selected treatments
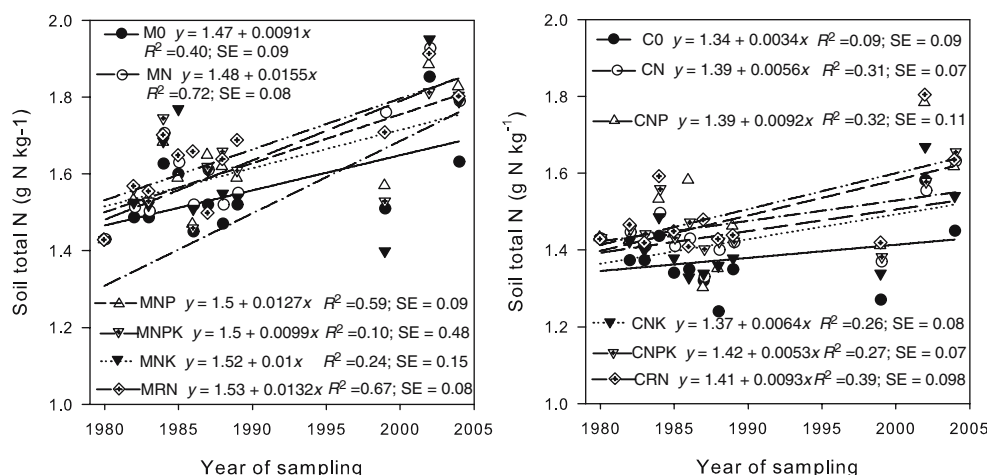
include that: (1) The control treatment (C0) supported 5.0 t ha^{-1} of rice yield and 2.2 t ha^{-1} of wheat yield per year as averaged over 24 years (Table 2), which were similar or higher than the comparable values reported from other long-term experiments in China and much higher than those reported from India (Yadav et al. 2000; Yaduvanshi and Swarup 2005), Nepal (Gami et al. 2001), Bangladesh (Saleque et al. 2004), Philippines (Cassman et al. 1996), and Vietnam (Tan et al. 1995); (2) SOC and soil total N showed increasing trend in all of the treatments (Figs. 3, 4 and Table 3); and (3) Rice yields showed increasing trends in all of the treatments (Figs. 1 and 2). Although wheat yield was slightly declining over the years in CNPK and MNPK treatments, because of the initially recommended fertilization rates, the declining trends were insignificant, with respective slopes of 0.0064 and 0.0087 t ha^{-1} year^{-1}.

Dawe et al. (2000) analyzed the yield trend of rice and wheat from seven rice–wheat long-term experiments (two in China and five in India) where recommended rates of N, P, and K were applied. They found that five sites showed a declining trend of rice yield, and two sites showed a declining trend of wheat, but the declining trend was statistically significant only in one site (Pantnagar, India). The declining trend was attributed to soil properties affected by prolonged soil wetness or soil nutrient depletion. Similarly, Ladha et al. (2003b) analyzed the yield trend of rice and wheat from 33 rice–wheat long-term experiments in Asian countries (three sites only from China). They found that 22 and 6% of the sites showed a significant declining trend of rice and wheat yields, respectively. Depletion of soil K was considered as the major reason for the yield declines. Data from the present experimental site, which have never been included in previous reports, indicated that rice yield showed an increasing trend and wheat yield showed stagnation or insignificant declining trend in CNPK and MNPK treatments (Figs. 1 and 2). Our data indicated that wheat yield stagnation or insignificant decline in CNPK and MNPK treatment was paralleled to the decline of NH$_4$OA-extractable K (Fig. 6), indicating that K fertilizer rates were

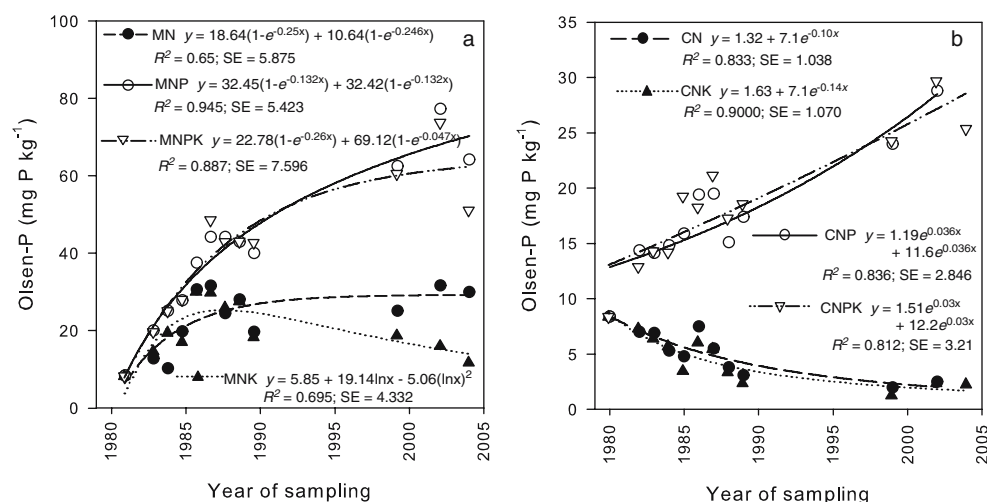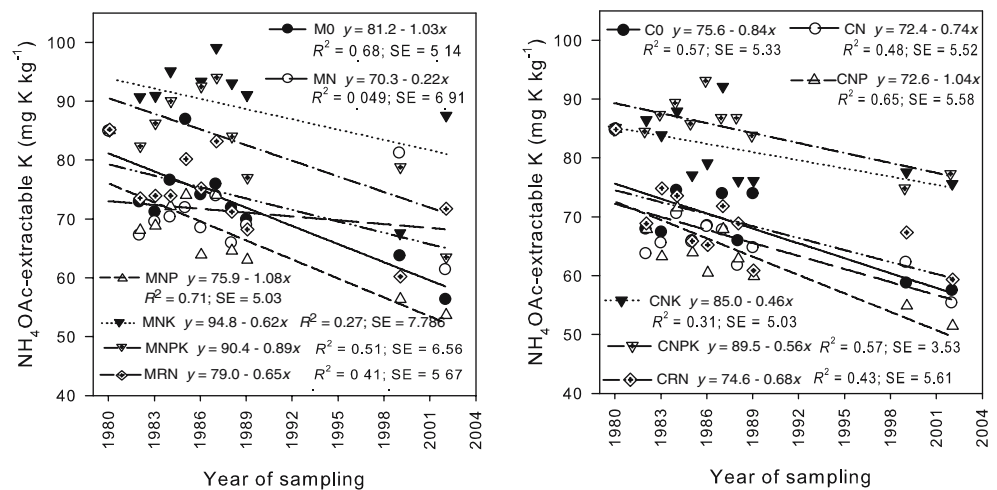**Fig. 5** Trend of Olsen-P over 24 years in selected treatments

Fig. 6 Trend of NH$_4$OAc-extractable K in soils of different treatments

insufficient and consequently causing wheat yield decline, although there was marginal K surplus in MNPK treatment (Table 5).

The SYI, originally developed by Singh et al. (1990) and widely used by other authors (Yadav et al. 2000; Yamoah et al. 2002; Prabhu et al. 2003; Manna et al. 2005; Sharma et al. 2005), was used to assess the effects of agricultural practices on crop yield sustainability. High SYI indicates the stable production of crop yields in a given set of agricultural practice. Data in Table 2 revealed that SYIs were consistently higher for rice (0.57 on average) than those for wheat (0.44 on average), suggesting rice yields are more sustainable than those of wheat at this location. SYIs

in MNPK and CNPK treatments were, among all the treatments in the respective block groups, the most sustainable treatments in terms of yield stability because their SYIs were the highest for both rice and wheat (Table 2). MNP was the least sustainable treatment as its SYI was the lowest for both rice and wheat in manure-treated groups. Because MNPK and MNP treatments differed in K input from a nutritional viewpoint, it was therefore concluded that K fertilization was necessary for yield sustainability in the ecosystem. The CRN showed the highest SYI for rice but the lowest for wheat within chemical fertilizer treatment group (Table 2). Similarly, MRN showed the highest SYI for rice but low (not the

Table 5 Nutrient balance sheet and apparent use efficiencies averaged over 24 years

Treatment	Total input (kg ha^{-1} year^{-1})			Recovered from above-ground biomass (kg ha^{-1} year^{-1})			Surplus/deficit (−; kg ha^{-1} year^{-1})			Apparent use efficiency (%)			Yield increment per unit of nutrient applied[a] (kg grain kg^{-1} nutrient)		
	N	P	K	N	P	K	N	P	K	N	P	K	N	P	K
M0	103.1	82.7	70.1	178.9	40.8	140.8	−75.8	41.9	−70.7	43.7	12.7	53.3			
MN	325.3	82.7	70.1	236.7	43.2	149.6	88.6	39.5	−79.5	31.6	15.6	65.9	5.7		
MNP	325.3	136.4	70.1	244.2	44.6	145.8	81.1	91.8	−75.7	33.9	10.5	60.5		1	
MNK	325.3	82.7	201.2	252.9	44.6	195.9	72.4	38.1	5.3	36.6	17.3	45.9			4.2
MPK	103.1	136.4	201.2	189.5	42.4	167.4	−86.4	94	33.8	54	8.9	31.8			
MNPK	325.3	136.4	201.2	253.3	47.6	196.6	72	88.8	4.6	36.7	12.6	46.3	6. 8	4.4	5.6
MRN	365.9	88.2	130.8	251.7	44.2	168.6	114.2	44	−37.8	32.2	15.8	49.8			
C0				133.8	30.3	103.4	−133.8	−30.3	−103.4						
CN	229.9			201.9	36.5	117.8	28	−36.5	−117.8	29.6			8.7		
CNP	229.9	55.8		212.5	39.1	126.6	17.4	16.7	−126.6	34.2	15.8			9.5	
CNK	229.9		137.5	216.5	37.4	160.2	13.4	−37.4	−22.7	35.9		41.3			3.1
CPK		55.8	137.5	142.3	34.7	129.5	−142.3	21.1	8.0		7.8	18.9			
CNPK	229.9	55.8	137.5	223.2	42.5	171.5	6.7	13.3	−34.0	38.9	21.9	49.5	11.1	12.5	4.3
CRN	270.5	5.5	59.8	223.2	38.9	134.4	47.3	−33.4	−74.6	33	156.8	51.8			

[a] Defined as the grain yield increment (rice + wheat) per unit of nutrient applied, which were calculated on the basis of one-to-one comparison between appropriate treatments.

lowest) SYI for wheat. These comparisons suggested that straw incorporation was beneficial to rice but not to wheat in the ecosystem. Currently, the rice straw is incorporated half in the rice season and half in the wheat season (~4,500 kg ha^{-1} year^{-1} in total), which should therefore be changed to incorporate in the rice season only.

Yadav et al. (2000) summarized the SYI values from six long-term experiment sites in India. They reported that the averaged SYI values over the sites in the treatment of 100% dose of recommended NPK were 0.66 for rice and 0.68 for wheat, which were much higher than the values reported in present paper (Table 2). The averaged yields of rice and wheat in the corresponding treatments in the India sites were 4.6 and 3.9 t ha^{-1}, respectively. The rice yield was significantly lower than those reported in this paper, but the wheat yield was comparable. This comparison led us to conclude that the India sites were more favorable for wheat growth than the China site.

Both CNPK and MNPK treatments produced 6.6–6.8 t ha^{-1} of rice and 3.7–4.0 t ha^{-1} of wheat (Table 2), the highest averaged yields among the treatments in the respective treatment block groups. These yields were comparable with the yields of the region as well as the averaged yield complied from the wider area of China (Timsina and Connor 2001). Despite the statistically significant difference from the highest averaged yield (Table 2), the second highest averaged yield (both rice and wheat) in treatments CRN, CNP, and CNK, being 92–98% of the top yield, was still acceptably high, suggesting that P and K contributed only small yield increase in the soil despite the existence of positive interaction among N, P, and K nutrients. Meanwhile, CN and MN treatments produced 94–95% of the highest rice yield and 88% of the highest wheat yield, suggesting that P and K fertilization was more important for wheat than for rice. Thus P and K fertilizers should be preferentially applied in the wheat season.

Nutrient balance sheet showed that there were large P surpluses in all P-treated plots (Table 5). Soil Olsen-P showed a significantly increasing trend in all P-treated plots but declining trend in all non-P-treated plots (Fig. 5 and Table 4). However, the increasing trend of soil Olsen-P did not alter the declining trend of wheat yield (Figs. 1 and 2), suggesting that the increased Olsen-P was wasteful. These data indicated that the current P fertilization rates were overdosed. Over-accumulation of P in surface soil will lead to not only economic losses but also environmental risks, because it could be transported to nearby water bodies via runoff, drainage, and leaching (Sharpley 1995; Sharpley et al. 1995). It is therefore suggested that the current P fertilization rate be reduced. Using the data in Table 5 and assuming that the amount of P absorbed (42.5 minus 37.5) and the averaged AUE of P ([21.9+15.8]/2) did not change substantially, the calculated appropriate P fertilization rate

was 27.6 kg P ha^{-1} year^{-1}. The rate of 30–40 kg P ha^{-1} year^{-1} would practically be an appropriate rate. The level of soil Olsen-P is another value for the evaluation of P fertilization rate. Initial Olsen-P in 0–15-cm soil was 8.4 mg P kg^{-1}, which was similar to the threshold levels reported by other authors (Nel et al. 1996; Shen et al. 2004). In addition, rice and wheat yields showed insignificant differences between P-treated and non-P treated plots during the 1981–1987 period until Olsen-P declined to 5.5 mg P kg^{-1} (details not shown). We therefore consider the level of Olsen-P at 8 mg P kg^{-1} as the sufficient level for the soil–crop ecosystem and recommend it as a reference value for soil testing.

In CN and CNK treatments, Olsen-P decreased to 2–3 mg P kg^{-1} in roughly 10 years after the experiment started (Fig. 5). This low level of Olsen-P adversely affected wheat yield in the following 14 years (Figs. 1 and 2), because CN and CNK (non-P-treated plots) showed more negative slopes than CNP and CNPK (P-treated plots). However, Olsen-P level as low as such did not affect rice yield, because CN and CNK treatments showed nearly identical slope as CNP and CNPK did (Figs. 1 and 2). The low soil redox potential during rice growth that facilitates P release from iron oxides (Szilas et al. 1998; Peretyazhko and Sposito 2005) may explain the results. However, the fact was that P assimilation rate by rice in non-P-treated plots was about 20 kg P ha^{-1} season^{-1} (detailed data not shown). It meant that the soil could somehow continuously supply P at such a high rate for at least 14 years under Olsen-P level as low as 2–3 mg P kg^{-1}. This phenomenon deserves further attention because it has been rarely found in other soils under similar ecosystem conditions. We hypothesized that beside Olsen-P, there were other yet-identified soil P pools that were large in size and ready to supply P to rice in the soil. The well-known procedure of soil P fractionation could be adopted to address this question, which is based on the premise that extractants of increasing acidity and alkalinity sequentially remove P of decreasing lability or bioavailability (Chang and Jackson 1957; Hedley et al. 1982; Sharpley 1995).

As for K, fertilization rate at 137.5 kg K ha^{-1} year^{-1} in CNPK treatment (Table 5) still depleted soil K at the rate of 34 kg K ha^{-1} year^{-1}, suggesting that the K fertilization rate was insufficient. In MNPK treatment, K fertilization rate was 201.2 kg K ha^{-1} year^{-1}, which led to marginal K surplus (Table 5) but significant decline of NH$_4$OAc-K (Fig. 6 and Table 4), suggesting that this K application rate was slightly lower than required. Therefore K application rate at 210–220 kg K ha^{-1} year^{-1} seemed to be a sufficient rate.

As for N, fertilization rate in CNPK treatment was considered as the rational rate. Four lines of evidences supported this conclusion: (1) Soil total N showed

increasing trend in all treatments (Fig. 4 and Table 4); (2) CNPK treatment gave 39% of apparent N use efficiency (Table 5), a value comparable with the values (33–38%) reported from a wide range of soils under rice–wheat ecosystem as summarized by Zhu (1997); (3) Small amount of N surplus existed in CNPK treatment (Table 5) but larger amount of N surplus existed in all treatments with higher N fertilization rates (manure + N treatments); and (4) The yield increment per kg N applied was 11.1 kg in CNPK treatment (Table 5), which was profitable enough for the local farmers. Nitrogen fertilizer rate in MNPK treatment seemed to be too high because it resulted in not only larger N surplus in soil but also lower yield increment per kg N applied, as compared to CNPK treatment.

SOC content is probably the most important index of soil fertility and sustainability under a given soil-crop-climate ecosystem (Tiessen 1994; Reeves 1997). In the present experiment, SOC in all treatments showed increasing trends, even in control treatment (Fig. 3), consistent with the reports by other authors on SOC storage in paddy soils in China (Cai 1996; Pan et al. 2003; Wu et al. 2003; Song et al. 2005). Similar trends but in different extents has been reported in long-term experiments from other countries such as Nepal (Gami et al. 2001) and India (Yadvinder-Singh et al. 2004; Manna et al. 2005). Yadav et al. (2000) summarized results of long-term experiments from six different locations in India under rice–wheat conditions and found the SOC trends were site-dependent. However many papers reported that long-term fertilizer applications resulted in loss of organic matter under dryland-cropping ecosystems (Jenkinson 1991; Nel et al. 1996; Aref and Wander 1998). The possible reasons for the increasing trend of SOC in rice-based ecosystems include deposition of eroded materials from uplands, multiple cropping, favorable moisture regime, low decomposition rate, and high input of roots and other biomass (Lal 2004b). For whatever reason, the increase in SOC in chemical fertilizer-treated plots indicated the high sustainability of the soil. It also indicated that the chemical fertilization did not substantially decrease the sustainability. The SOC accumulation potential, as calculated by simulation curves in Fig. 3, was positively correlated with C input (Table 3), although the C input calculated was more in relative than in absolute sense.

The patterns of soil fertility development in term of SOC contents were changed after the shift from the traditional manure-based to the chemical fertilizer-based managements. Before the experiment, the soil had been used for many years for growing rice and wheat. Fertilizers were basically farmyard manure, river mud, legume plant materials, and remaining ashes from straw as a cooking fuel. Chemical fertilizers were used only in a few locations in negligible quantities (Ellis and Wang 1997). The M0 treatment in the present experiment was similar to these historic fertilizer managements, and the CNPK was representative of the currently widespread practices. According to the simulated SOC patterns (Fig. 3), the predicted maximal SOC in CNPK treatment was 16.22 g C kg^{-1} (13.71+2.51), being 0.69 g C kg^{-1} lower than the respective value in M0 treatment (16.91 g C kg^{-1}; Fig. 3). It took only 7 years for M0 treatment but 16 years for CNPK treatment to reach 99% of predicted maximal SOC content of the respective soils. These data suggested that, under the soil-crop-climate ecosystem, the shift from manure-based to chemical fertilizer-based management systems decreased the predicted maximal SOC levels and increased the time to arrive at the maximal levels, indicating the importance of manure application in maintaining soil fertility and C sequestration potential. Incorporation of rice straw had similar beneficial effects as manure application.

Soil pH was significantly decreased in all treatments except in the control, as compared with the initial value (Table 4). The lowest pH was 5.7 in MRN, MN, CRN, and CNPK treatments, 1.1 unit lower than the initial value, suggesting that fertilization had some effect on soil pH. However there was no correlation between soil pH decrease and the fertilizer managements.

Currently, manure application becomes rare and straw incorporation is an adoptable practice in the region. Taking the straw incorporation as the basic practice, N, P, and K fertilization rates could be further optimized. We recommend straw to be incorporated at 4,500 kg ha^{-1} in the ice season only, plus 190 kg N ha^{-1} year^{-1}, with 30–40 kg P ha^{-1} year^{-1}, and 150–160 kg K ha^{-1} year^{-1}. Two third of P and K should be allocated to the wheat season.

In summary, the results from the long-term experiment revealed that: (1) Under these soil-plant-climate conditions, no substantial adverse effects of the chemical fertilizations on soil fertility and sustainability were observed as far as N, P and K were applied in appropriate combinations; (2) Rice straw incorporation should only be practiced in rice season, as far as the yield sustainability is concerned; (3) K fertilization is essential for the yield sustainability. 4) P fertilization rate should be significantly cut down. Based on nutrient contents of rice straw and nutrient balance sheet (Table 3), and considering crop yield sustainability, soil fertility, and environmental effects all together, we suggest a straw incorporation rate of 4,500 kg ha^{-1} year^{-1} in rice season only, 190 kg N ha^{-1} year^{-1}, 30~40 kg P ha^{-1} year^{-1} mainly in rice season, and 150~160 kg K ha^{-1} year^{-1}. Further research on the unusual P supply capacity of the soil is needed.

References

Aref S, Wander MM (1998) Long-term trends of corn yield and soil organic matter in different crop sequences and soil fertility treatments on the morrow plots. Adv Agron 62:153–161

Bremner JM (1996) Nitrogen-total. In: Sparks DL, Page AL, Helmke PA, Leoppert RH, Soltanpour PN, Tabatabai MA, Johnston CT, Sumner ME (eds) Methods of soil analysis. Part 3. Chemical methods. Soil Science Society of America, Madison, WI, pp 1085–1121

Cai Z (1996) Effect of land use on organic carbon storage in soils in eastern China. Water Air Soil Pollut 91:383–393

Cao ZH, Ding JL, Hu ZY, Knicker H, Kogel-Knabner I, Yang LZ, Yin R, Lin XG, Dong YH (2006) Ancient paddy soils from the neolithic age in China's Yangtze River Delta. Naturwissenschaften 93:232–236

Cassman KG, Gines GC, Dizon MA, Samson MI, Alcantara JM (1996) Nitrogen-use efficiency in tropical lowland rice systems: contributions from indigenous and applied nitrogen. Field Crops Res 47:1–12

Chang SC, Jackson ML (1957) Fractionations of soil phosphorus. Soil Sci 84:133–144

Cornfield AH (1960) Ammonia released on treating soils with N sodium hydroxide as a possible means of predicting the nitrogen-supplying power of soils. Nature 187:260–261

Dawe D, Dobermann A, Moya P, Abdulrachman S, Bijay S, Lal P, Li SY, Lin B, Panaullah G, Sariam O, Singh Y, Swarup A, Tan PS, Zhen QX (2000) How widespread are yield declines in long-term rice experiments in Asia? Field Crops Res 66:175–193

Ellis EC, Wang SM (1997) Sustainable traditional agriculture in the Taihu Lake region of China. Agric Ecosyst Environ 61:177–193

Erda L, Yunfen L, Yue L (1997) Agricultural carbon cycle and greenhouse gas emissions in China. Nutr Cycl Agroecosyst 49:295–299

Gami SK, Ladha JK, Pathak H, Shah MP, Pasuquin E, Pandey SP, Hobbs PR, Joshy D, Mishra R (2001) Long-term changes in yield and soil fertility in a twenty-year rice–wheat experiment in Nepal. Biol Fertil Soils 34:73–78

Hedley MJ, Stewart JWB, Chanhan BS (1982) Changes in inorganic and organic soil phosphorus fraction induced by cultivation practices and by laboratory incubations. Soil Sci Soc Am J 46:970–976

Jenkinson DS (1991) The Rothamsted long-term experiments: are they still of use?. Agron J 83:2–10

Ladha JK, Pathak H, Padre AT, Dawe D, Gupta RK (2003a) Productivity trends in intensive rice–wheat cropping systems in Asia. In: Ladha JK, Hill JE, Duxbury JM, Gupta RK, Buresh RJ (eds) Improving the productivity and sustainability of rice–wheat systems: issues and impacts. ASA special publication 65, ASA-CSSA-SSSA, Madison, USA, pp 45–76

Ladha JK, Dawe D, Pathak H, Padre AT, Yadav RL, Singh B, Singh Y, Singh P, Kundu AL, Sakal R, Ram N, Regmi AP, Gami SK, Bhandari AL, Amin R, Yadav CR, Bhattarai EM, Das S, Aggarwal HP, Gupta RK, Hobbs PR (2003b) How extensive are yield declines in long-term rice–wheat experiments in Asia?. Field Crops Res 81:159–180

Lal R (2004a) Soil carbon sequestration to mitigate climate change. Geoderma 123:1–22

Lal R (2004b) Offsetting China's CO_2 emission by soil carbon sequestration. Clim Change 65:263–275

Manna MC, Swarup A, Wanjari RH, Ravankar HN, Mishra B, Saha MN, Singh YV, Sahi DK, Sarap PA (2005) Long-term effect of fertilizer and manure application on soil organic carbon storage, soil quality and yield sustainability under sub-humid and semi-arid tropical India. Field Crops Res 93:264–280

Nel PC, Barnard RO, Steynberg RE, de Beer JM, Groeneveld HT (1996) Trends in maize grain yields in a long-term fertilizer trial. Field Crops Res 47:53–64

Nelson DW, Sommers LE (1996) Total carbon, organic carbon and organic matter. In: Sparks DL, Page AL, Helmke PA, Loeppert RH, Soltanpour PN, Tabatabai MA, Johnston CT, Sumner ME (eds) Methods of soil analysis. Part 3. Chemical methods. Soil Science Society of America, Madison, WI, pp 961–1010

Olsen RS, Cole VC, Watanabey FS, Dean LA (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. US Department of Agricultural Circulation, p 939

Pan GX, Li LQ, Wu LS, Zhang XH (2003) Storage and sequestration potential of topsoil organic carbon in China's paddy soils. Global Change Biol 10:79–92

Peretyazhko T, Sposito G (2005) Iron (III) reduction and phosphorous solubilization in humid tropical forest soils. Geochim Cosmochim Acta 69:3643–3652

Prabhu AS, Filippi MC, Zimmermann FJP (2003) Cultivar response to fungicide application in relation to rice blast control, productivity and sustainability. Pesq Agropec Bras 38:11–17

Reeves D (1997) The role of soil organic matter in maintaining soil quality in continuous cropping systems. Soil Tillage Res 43:131–167

Saleque MA, Abedin MJ, Bhuiyan NI, Zaman SK, Panaullah GM (2004) Long-term effects of inorganic and organic fertilizer sources on yield and nutrient accumulation of lowland rice. Field Crops Res 86:53–65

Shan YH, Yang LZ, Yan TM, Wang JG (2005) Downward movement of phosphorus in paddy soil installed in large-scale monolith lysimeters. Agr Ecosyst Environ 111:270–278

Sharma KL, Mandal UK, Srinivas K, Vittal KPR, Mandal B, Grace JK, Ramesh V (2005) Long-term soil management effects on crop yields and soil quality in a dryland Alfisol. Soil Tillage Res 83:246–259

Sharpley AN (1995) Soil phosphorus dynamics: agronomic and environmental impacts. Ecol Eng 5:261–279

Sharpley AN, Robinson JS, Smith SJ (1995) Bioavailable phosphorus dynamics in agricultural soils and effects on water quality. Geoderma 67:1–15

Shen J, Li R, Zhang F, Fan J, Tang C, Rengel Z (2004) Crop yields, soil fertility and phosphorus fractions in response to long-term fertilization under the rice monoculture system on a calcareous soil. Field Crops Res 86:225–238

Shi XZ, Yu DS, Warner ED, Pan XZ, Petersen GW, Gong ZT, Weindorf DC (2004) Soil database of 1:1,000,000 digital soil survey and reference system of the Chinese genetic soil classification system. Soil Surv Horiz 45:129–136

Singh RP, Das SK, Bhaskara Rao UM, Narayana Reddy M (1990) Towards sustainable dryland agricultural practices. CRIDA, Hyderabad, India

Song GH, Li LQ, Pan GX, Zhang Q (2005) Topsoil organic carbon storage of China and its loss by cultivation. Biogeochemistry 74:47–62

Szilas CP, Borgaard OK, Hansen HCB (1998) Potential iron and phosphate mobilization during flooding of soil material. Water Air Soil Pollut 106:97–109

Tan PS, Anh TN, Luat NV, Puckridge DW (1995) Yield trends of a long-term NPK experiment for intensive rice monoculture in the Mekong River Delta of Vietnam. Field Crops Res 42:101–109

Tiessen H (1994) The role of soil organic matter in sustaining soil fertility. Nature 371:783–785

Timsina J, Connor DJ (2001) Productivity and management of rice–wheat cropping systems: issues and challenges. Field Crops Res 69:93–132

Wang WJ, Smith CJ, Chalk PM, Chen D (2001) Evaluating chemical and physical indices of nitrogen mineralization capacity with an unequivocal reference. Soil Sci Soc Am J 65:368–376

Wu HB, Guo ZT, Peng CH (2003) Land use induced changes of organic carbon storage in soils of China. Glob Chang Biol 9:305–315

Yadav RL, Dwivedi BS, Pandey PS (2000) Rice–wheat cropping system: assessment of sustainability under green manuring and chemical fertilizer. Field Crops Res 65:15–30

Yaduvanshi NPS, Swarup A (2005) Effect of continuous use of sodic irrigation water with and without gypsum, farmyard manure, press mud and fertilizer on soil properties and yields of rice and wheat in a long term experiment. Nutr Cycl Agroecosyst 73:111–118

Yadvinder-Singh, Bijay-Singh, Ladha JK, Khind CS, Gupta RK, Meelu OP, Pasuquin E (2004) Long-term effects of organic inputs on yield and soil fertility in rice–wheat rotation. Soil Sci Soc Am J 68:845–853

Yamoah CF, Bationo A, Shapiro B, Koala S (2002) Trend and stability analyses of millet yields treated with fertilizer and crop residues in the Sahel. Field Crops Res 75:53–62

Yoshida S, Forno DA, Cock JH, Gomez KA (1976) Laboratory manual for physicological studies of rice, 3rd edn. Int Rice Res Inst, PO Box 933, Manila, Philippines

Zhang HC, Cao ZH, Shen QR, Wong MH (2003a) Effect of phosphate fertilizer application on phosphorus (P) losses from paddy soils in Taihu Lake region. I. Effect of phosphate fertilizer rate on P losses from paddy soil. Chemosphere 50: 695–701

Zhang HC, Cao ZH, Wang GP, Zhang HA, Wong MH (2003b) Winter runoff losses of phosphorus from paddy soils in the Taihu Lake Region of South China. Chemosphere 52:1461–1466

Zhu ZL (1997) Fate and management of fertilizer nitrogen in agroecosystem. In: Zhu ZL, Wen QX, Freney JR (eds) Nitrogen in soils of China. Kluwer, Dordrecht, pp 239–279