



Long-term changes in organic carbon and nutrients of an Ultisol under rice cropping in southeast China

Mingkui Zhang*, Zhenli He

Department of Resource Science, College of Natural Resource and Environmental Sciences, Huajiachi Campus, Zhejiang University, Hangzhou 310029, PR China

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Abstract

It is well known that the availability of nutrients in red soils (equivalent to Ultisols and some of the Alfisols and Oxisols in the soil taxonomy of USA) changes after conversion of upland to irrigated rice (*Oryza sativa* L.) production, but long-term changes in carbon (C) and nutrients are not well documented. To characterize changes in C and nutrients in paddy fields on a Quaternary red clay (clayey, kaolinitic thermic typic plinthudults) during long-term rice cropping, we measured total C, nitrogen (N), phosphorus (P) and potassium (K), particulate organic matter (POM), N in the POM, potential mineralized N, available P, as well as other properties (pH, exchangeable cations, effective cation exchange capacity (ECEC), aggregate stability) in the plow layer (0–15 cm) of 66 rice fields with rice-cultivation time ranging from 2 to 100 years. Total C, N, and P distributions were also determined in six soil profiles with rice-cultivation times of 2, 5, 19, 48, 68, and 100 years, respectively. Significant increases in organic C, total N, and P concentrations in plow layer were found in the first 30–40 years of rice cropping, accompanied by increases in available P and potential mineralized N, exchangeable Ca, Mg, Na, base saturation, and water-stable aggregates, and decreases in total K and clay content. The C/N ratio of organic matter tended to decrease in the first 20 years of rice cropping, and remained constant at approximately 10, whereas the ratio of humic acid to fulvic acid (H/F ratio) increased gradually to about 1 after 50 years of rice cropping. Long-term rice cropping elevated C, N, and P in the plow layer and increased accumulation of C, N, and P in the subsurface soils. The results indicate: (i) long-term rice cropping improved soil fertility as evidenced by neutralization of soil acidity, and increases in ECEC, organic C content, and H/F ratio; (ii) imbalance of fertilization by high N and low K, as revealed by decreased soil K and increased soil N; (iii) long-term rice cropping caused downward movement of organic C, N, and P, which may result in environmental impacts.

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1. Introduction

Red soils occupy approximately 1.28 million km² in southern China and are a vital natural resource in

the region (Li, 1983). These soils have been subjected to intensive weathering and mineral nutrients, including calcium (Ca), magnesium (Mg), and potassium (K), in the soils are mostly eluted. In addition, the red soil region, being the most densely populated, is under great pressure to increase upland in order to meet an increasing demand for food and fiber, which causes severe soil erosion. Upland cultivation and soil ero-

* Corresponding author. Tel.: +86-571-8697-1146; fax: +86-571-8697-1152.

E-mail address: mkzhang@zju.edu.cn (M.K. Zhang).

sion have substantially decreased organic C and other nutrients in the red soils and have increased soil acidity. Low organic C and high acidity are major soil constraints that limit crop growth in the red soil regions. In most cases, organic C in the surface layer in these soils was generally below 7.5 g kg^{-1} (Yu, 1994). The utilization efficiency of applied fertilizers is very low in the eroded soils (<10% for P and <30% for N and K). Low nutrient levels, acidity, chemical fixation of P, and severe erosion are the major reason responsible for the low nutrient utilization efficiency (Li, 1983).

In order to prevent the soils from further degradation, conversion from upland to irrigated paddy fields, by leveling the land and developing irrigation systems, has been recognized as an effective approach in areas with a sufficient supply of irrigation water. The practice of converting upland red soils to irrigated paddy fields in some areas (e.g. the Jingqu Basin, Zhejiang Province, China) has been implemented for more than a century. Periodic irrigation, drainage, fertilization, and tillage during the process of rice production has resulted in rapid changes in soil characteristics. Studies demonstrated that the introduction of irrigated rice-cropping practices improved soil conditions, including increased organic matter C and pH (Li, 1992). Available P increased rapidly following rice cropping, because of reduction of Fe (III) compounds that liberate sorbed and coprecipitated P (De Datta, 1983; Diamond, 1985; Yu, 1994). It is commonly accepted that implementation of rice-cropping practices would enhance accumulation of soil organic C (Lal, 2002). Significant increases in grain production are generally recorded in the first 5 to 10 years of rice cropping (Yu, 1994). Some reports suggested that such changes were attributable to the differences in soil moisture conditions between upland and irrigated rice production systems (Yu, 1994). Differences in fertilizer use efficiency were also observed between these two systems, since irrigated rice practice could increase P availability and reduce runoff nutrient loss from the soils as compared with upland (Li, 1992). Irrigated rice cropping has been suggested as a measure to improve soil conditions (Yu, 1994). However, the rate at which improvement proceeds has not been well addressed, particularly the time required for significant changes to occur. Understanding time requirements for soil properties to be substantially improved after transformation

of upland to irrigated paddy fields is important for evaluating the potential benefits of rice cropping over upland culture and for developing rational management practices.

Agricultural land use has a marked influence on the content and distribution of organic C and nutrient pools (Compton et al., 1998; Ellert and Bettany, 1995; McCarty et al., 1998; Neufeldt et al., 2000; Murillo, 2001; Pulleman et al., 2000). Cultivation can change soil organic C by increasing soil organic C decomposition or synthesis rates (Blevins et al., 1983; Bowman et al., 1990; Campbell et al., 1996; Drury et al., 1998; Franzluebbers et al., 1999; Halin et al., 1990; Hill, 1990; Ismail et al., 1994). Recently, storage and dynamics of C and nutrients in soils have received increasing attention because of the importance of soil organic C and nutrient pools in soil fertility sustainability and environmental quality (Griegal and Ohmann, 1992). Lal et al. (1998) point out that the value of soil organic C is related to more than its improvement in the water-holding capacity and nutrient availability in the soil, its hidden value comes in its ability to help mitigate the greenhouse effect on the environment. Undoubtedly, rice cropping, as an important land use, has significant effects on C, and N cycling around the globe. It was also well established that transformation patterns of nutrients are significantly changed after conversion of upland red soils to irrigated paddy fields (Li, 1983; Yu, 1994). However, to date, much of the published information on the impact of this land use conversion practices on nutrients has been based on short time changes, and minimal information is available regarding the long-term changes in organic C and nutrients and their vertical distribution. The objective of this study was to characterize long-term changes of organic C and nutrients in paddy fields on a quaternary red clay after conversion of upland to irrigated rice fields.

2. Materials and methods

2.1. Sampling

This study was carried out in irrigated paddy fields on a quaternary red clay that is extensively distributed in southern China. Previous land use was upland used

for production of wheat (*Triticum aestivum* L.), and sweet potato (*Ipomoea batatas* L.) or wasteland with low soil quality resulting from intensive soil erosion. The grain yield of wheat upland areas was generally below 2.5 Mg ha^{-1} (Yu, 1994). The conversion of upland to irrigated paddy field was carried out by leveling the land and developing the irrigation system. Samples of both surface and profile soils (to 1.5 m) were collected from different fields with a rice cropping history of 2–100 years in an area of about 950 km^2 in the Jingqu Basin, the southeast of China (approximately $29^{\circ}18'N$, $119^{\circ}55'E$). The area receives an average of 1667 mm annual precipitation with 47% in April to June. Site elevation is 60–120 m above sea level, and open pan evaporation is 990 mm per year. The soil before rice cropping was a red soil that could be classified as clayey, kaolinitic thermic typic plinthudults under the US Taxonomy (Soil Survey Staff, 1998). Each year, rice was harvested twice (July and October), and the soil was fallowed or planted with oilseed rape (*Brassica napus* L.) in winter. Early rice is grown from April to mid- or late July, whereas late rice is grown from mid-July to late October. Land preparation is performed on wet soils with tractors. Rivers and reservoirs irrigate all rice fields. During the rice growth, the fields were maintained under a wet or moist soil condition. Fertilization rates for the different fields in this area were similar, annual average rate of inorganic N, P, K were 290, 84, and 28 kg ha^{-1} , respectively, and organic manure 2.0 Mg ha^{-1} , based on investigation of 66 fields. The N, P, and K concentrations in the organic manure were 10.0–46.7, 3.5–22.5, and 12.2–25.0 g kg^{-1} , respectively. About one fourth of crop residues ($3 \text{ Mg ha}^{-1} \text{ year}^{-1}$) were returned to the fields. In addition to the application of N, P, and K, it has been common for the rice production in the areas to occasionally apply lime materials.

Fields with different rice cropping periods were selected after consultation with the farmers. The collection of soil samples was carried out in two stages. The first sample collection occurred in the fall of 1997 when soil samples from 66 fields, which had been rice-cropped and irrigated for 2–100 years, were collected. For each field, five locations were selected across the field. At each location, a 50-cm^2 core sample was taken at a depth of 15 cm using a hand sampler (8 cm diameter). The samples for each field

were bulked to form one composite soil sample and air-dried. In the fall of 1998, six soil profiles with rice cropping periods of 2, 5, 19, 48, 68, and 100 years, respectively, were sampled. The soil profiles were sampled to 150 cm at 10-cm increments. All surface samples were operationally grouped into five periods: i.e., Period I (0–5 years), Period II (6–15 years), Period III (16–30 years), Period IV (31–50 years) and Period V (51–100 years). All the sampled paddy soils were derived from the quaternary red clay and had been subjected to alternate wetting and drying for varying years. After removal of visible pieces of crop residue, the soil samples were then sieved through a 2-mm screen, mixed and stored at room temperature prior to chemical analyses.

2.2. Soil analyses

Soil pH was measured in a 1:1 (w/w) soil/distilled water suspension. Soil clay content was estimated by the hydrometer method after the soil was pre-treated with H_2O_2 and dispersed overnight in Na-hexametaphosphate (Institute of Soil Science, Chinese Academy of Sciences, 1978). Aggregate stability measurements were performed according to the procedure of the Institute of Soil Science, Chinese Academy of Sciences (1978). Soil bulk density for the soil profile samples was determined in each location for each sampling depth by collecting 5-cm diameter cores. Total P was analyzed using the molybdate blue method after digestion in nitric acid and perchloric acid (Agricultural Chemistry Committee of China, 1983).

Particulate organic matter was separated from samples by dispersing 20-g soil samples with 50 ml of sodium hexametaphosphate solution ($5 \text{ g l}^{-1} \text{ H}_2\text{O}$). The suspensions were shaken at high speed ($150 \text{ cycles min}^{-1}$) on an end-to-end shaker for 1 h and rinsed through a $53 \mu\text{m}$ sieve. The material collected on the sieve was retained and dried at 70°C . The dried POM fraction was ground to pass through a 0.125 mm sieve. Total C and N contents of the whole soil and the POM fraction were determined by wet digestion and micro-Kjeldahl procedures, respectively (Agricultural Chemistry Committee of China, 1983). Potentially mineralized N (PMN) was determined by the anaerobic incubation method after Waring and Bremner (1964). Soil samples (6 g) were placed in a

50 ml centrifuge tube, saturated with 10 ml of deionized water, and incubated at 40 °C for 7 days. Then, 40 ml of 0.625 mol l⁻¹ K₂SO₄ was added to give a final concentration of approximately 0.5 mol l⁻¹. The tube was shaken for 1 h on a reciprocating shaker and the suspension was filtered. The experiment was performed on subsamples, but without the incubation step. Ammonium was determined colorimetrically by the indophenol blue method (Sims et al., 1995). The PMN was obtained as the difference in the amount of ammonium between the incubated and the nonincubated soil.

Olsen-P was extracted by shaking 2.5 g of air-dried soil for 30 min with 50 ml of 0.5 mol l⁻¹ NaHCO₃ (pH 8.5). An aliquot of the extract was analyzed for P with the molybdate blue method (Institute of Soil Science, Chinese Academy of Sciences, 1978). Sodium-hydroxide-extractable P was determined by shaking 1.0 g of soil with 50 ml of 0.1 mol l⁻¹ NaOH overnight and then centrifuging. An aliquot of the NaOH extract was acidified with 1 mol l⁻¹ H₂SO₄ and centrifuged for 30 min to precipitate the organic matter. The supernatant was then analyzed for NaOH-IP (inorganic P). Aliquots of the NaOH extract were digested with acidified ammonium persulfate for 1 h and then analyzed for total P (TP) (Institute of Soil Science, Chinese Academy of Sciences, 1978). Extractable organic P (OP) was calculated as the difference between extractable TP and IP (Tiessen and Moir, 1993). Humic acid (HA) and fulvic acid (FA) were first extracted with 0.1 mol l⁻¹ NaOH and then fractionated by acidification with HCl and determined by wet combustion (Institute of Soil Science, Chinese Academy of Sciences, 1978). Exchangeable Ca, Mg, K and Na were extracted with 1 mol l⁻¹ NH₄OAc at pH 7.0, exchangeable Al and H were extracted with 1

mol l⁻¹ KCl, and effective cation exchange capacity (ECEC) was determined by summation of the cations (Sumner and Miller, 1996). Base saturation was calculated as a percentage of exchangeable bases (K, Na, Ca, and Mg) in the ECEC. Total K was determined by flame atomic absorption spectrometry (Perkin Elmer 306, Shelton, CT) after the soil samples were decomposed by fusion with NaOH (Agricultural Chemistry Committee of China, 1983).

2.3. Statistical methods

Mean separation of soil properties among the five rice fields with varying rice-cropping periods were obtained by Bayes least significant difference. Simple correlation analysis between variables was performed using the SAS programs (SAS Institute, 1998).

3. Results and discussion

3.1. Soil characteristics

Exchangeable cations, ECEC, base saturation, pH, contents of clay and >0.25 mm water-stable aggregates are presented in Table 1. The soil properties varied widely with the time of rice cropping. Generally, exchangeable Ca, Mg, Na, pH, base saturation, and >0.25 mm water-stable aggregates increased, and exchangeable Al+H, and clay content decreased with years of rice cropping. The most rapid changes of the abovementioned properties with the time of rice cropping occurred in the first 15–30 years.

The increased exchangeable Ca, Mg, Na, pH, and base saturation were mainly due to lime application. Organic manure usually contains considerable Ca,

Table 1
Mean soil exchangeable cations and pH in different rice cropping periods

Periods	pH	Exchangeable cations (mol _c kg ⁻¹)					ECEC	Base saturation (%)	Clay (g kg ⁻¹)	>0.25 mm aggregate (%)
		Ca	Mg	Na	K	Al+H				
I (0–5 years)	5.69d	2.13c	1.12e	0.25c	0.45a	5.05a	9.00d	43.5c	342a	48.0d
II (6–15 years)	6.26c	4.20b	1.40d	0.26bc	0.44a	3.55b	9.86c	63.6b	292b	71.3c
III (16–30 years)	6.65b	6.79a	1.78c	0.30ab	0.40a	1.61c	10.9b	85.2a	260c	80.4b
IV (31–50 years)	6.72ab	6.88a	2.33b	0.34a	0.42a	1.68c	11.8a	85.9a	245c	87.7a
V (51–100 years)	6.84a	7.08a	2.88a	0.34a	0.38a	1.54c	12.1a	87.3a	217d	88.0a

Means in a column followed by the same letter were not significantly different at $p < 0.05$.

Mg, and Na, which, in part, contributed to the increases in the exchangeable Ca, Mg, Na, and base saturation. In addition, irrigated water also brought small amounts of Ca, Mg, and Na to the soils. The increased >0.25 mm water-stable aggregates with time of rice cropping were probably related to an increase in soil organic C (Zhang et al., 1997). Water cultivation and irrigation facilitated clay movement downward, resulting in decreased clay content in the surface soils. Clay eluviation was thought as a main pedogenic process in paddy soils (Zhu, 1981).

3.2. Changes in total carbon and nitrogen

Soil organic C content in the surface layer (0–15 cm) increased gradually in the first 30 years of rice cropping (Fig. 1). After 30 years of rice cropping, soil organic C reached a relatively stable level. This level appeared to be about 20 g kg^{-1} organic C, which was about threefold of those in soils of the Period I (0–5 years) (Table 2). The increase in organic C with years of rice cropping was the greatest during the 2–15-year period, and became smaller thereafter. The differences in soil organic C among Period I (0–5 years), Period II (6–15 years), Period III (16–30 years), Period IV (31–50 years) were statistically significant, whereas no significant difference was found between Period IV (31–50 years) and Period V (51–100 years) (Table 2).

The amount of organic C stored in paddy soils is greater than upland soils because of different biochemical processes and mechanisms mainly caused by the presence of flooded water in paddy soils (Guo and Lin, 2001). Under anaerobic conditions, humication coefficient (a fraction of remaining organic C portions in total quantities of added organic C 1 year after being amended) is higher under flooding than in nonflooding conditions. Both decomposition of amended organic materials and mineralization rates of native soil organic C are considerably retarded compared with those under aerobic conditions. Therefore, flooding has a tendency to enhance organic C accumulation in the soils.

The end of organic C increase in the surface soils after 30 years of rice cropping was related to a balance on input and output of organic C. The input of organic C by organic manure and rice straw was relatively constant. As such, the net accumulation rate of

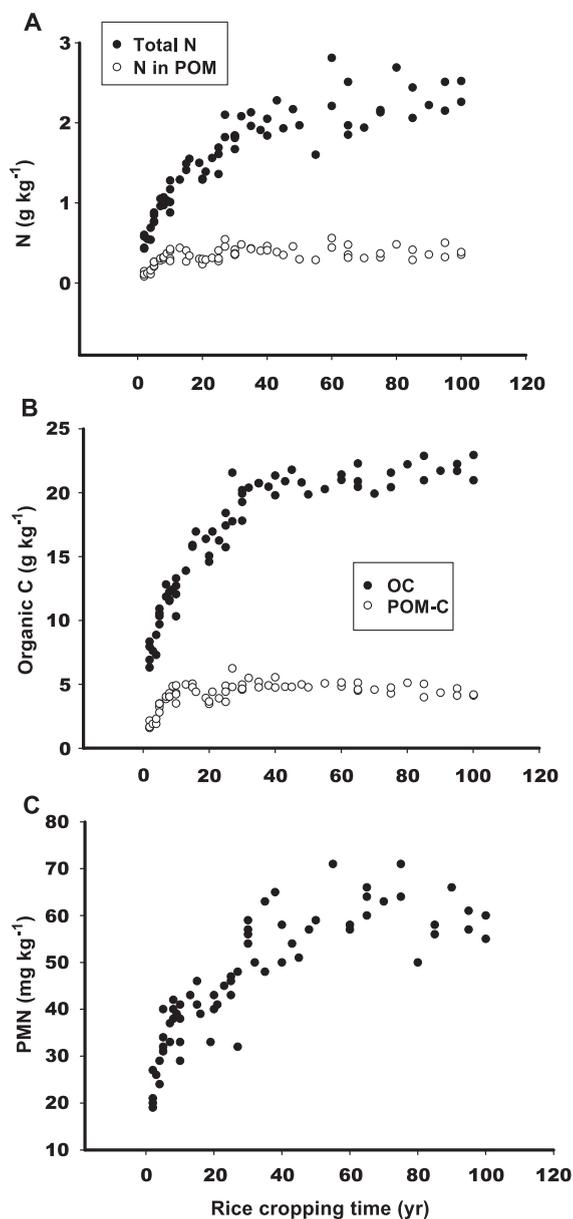


Fig. 1. Concentrations of organic C and N in the surface soil layer (0–15 cm) as a function of rice cropping time: (A) total N and N in particulate organic matter (POM); (B) organic C (OC) and POM-C; (C) potential mineralized N (PMN).

organic C reduced with increasing soil organic C level, because organic C mineralization and leaching downward from the surface layer increased with increasing organic C level in the soils. When the output of organic C (decomposition and leaching)

Table 2
Mean soil carbon and nitrogen fractions in different rice cropping periods

Periods	OC (g kg ⁻¹)	TN (g kg ⁻¹)	C/N	H/F	POM-C (g kg ⁻¹)	POM-N (g kg ⁻¹)	POM- C/OC	POM- N/TN	C/N in POM	PMN (mg kg ⁻¹)	PMN/TN (%)
I (0–5 years)	8.58d	0.65e	13.6a	0.46e	2.38c	0.16c	0.27b	0.24b	15.4a	27.5e	24.1b
II (6–15 years)	12.8c	1.12d	11.5b	0.60d	4.37b	0.34b	0.34a	0.30a	13.1b	38.4d	30.5a
III (16–30 years)	17.6b	1.62c	10.9bc	0.76c	4.44b	0.35ab	0.25bc	0.21c	12.9b	45.5c	21.5b
IV (31–50 years)	20.6a	2.03b	10.2bc	0.92b	4.62ab	0.41a	0.24c	0.20c	12.4b	55.4b	20.2bc
V (51–100 years)	21.4a	2.24a	9.7c	1.19a	5.01a	0.38ab	0.22d	0.17d	12.4b	61.0a	17.1c

OC, organic C; TN, total N; H/F, ratio of humic acid to fulvic acid; POM-C, particulate organic C; PMN, potentially mineralized N. Means in each column followed by the same letter were not significantly different at $p < 0.05$.

was close to the input, the change of soil organic C with time was minimal.

Changes of N in the surface soil layer (0–15 cm) after rice cropping followed a similar pattern of organic C (Table 2). However, the increase in N lasted much longer than organic C. Even after 30 years of rice cropping, N still gradually increased with time, although the increase during 31–100 years was much smaller as compared with the first 30 years. There was a very significant difference in total N levels among the five different periods (Table 2), indicating that total soil N maintained a steady increase up to 100 years of rice cropping. Greater accumulations of organic C and total N in the plow layer could be explained by increased input of plant residues, reduced decomposition rate of organic residues, and increased N fixation in the rice production system (Kundu and Ladha, 1995; Roger and Ladha, 1992). The fast accumulation of N was, in part, due to high input of N fertilizer. In southern China, chemical fertilizer N is often overapplied in the rice production systems (Zhu, 1998).

3.3. Change of particulate organic matter

The POM is an important organic matter pool of intermediate decomposition and is usually regarded as a sensitive indicator of soil management (Cambardella and Elliott, 1992; Franzluebbers and Arshad, 1997; Wander et al., 1998; Wander and Bidart, 2000). Researchers have shown that tillage preferentially affects macro-organic matter and other labile components of the total organic matter pool (Beare et al., 1994; Cambardella and Elliott, 1992; Elliott, 1986; Tiessen et al., 1984). The POM, which is often related to the amount of residue, litter, and shallow roots,

increased with years of rice cropping (Table 2). Period V (51–100 years) rice field had the highest POM-C, whereas Period I (0–5 years) rice field had the lowest. The difference in POM-C could be attributed to an increase in biomass production in the rice system, especially the first 10 years, which provided more litter and roots for POM formation. The data showed that POM-M accounted for about 18–39% of the total soil organic C. Data for POM-N was similar to that for the POM-C, and the ratio of POM-N/TN varied from 0.14 to 0.36. Variation of either POM-C/OC or POM-N/TN with years of rice cropping was different from that of the total organic C and N contents, they increased rapidly from Period I (0–5 years) to Period II (6–15 years), and then decreased gradually with extended time. This may be due to the difference in changing patterns of the POM-C and organic C. After 15 years of rice cropping, organic C continued to increase, but POM-C was relatively constant (Fig. 1).

With increasing total N and POM-N, potential mineralizable N (PMN) in paddy soils increased with increasing years of rice cropping. Similar to total N, the PMN quickly increased in the first 15 years, reached 50–60 mg kg⁻¹ at 40 years, and then, the increase in the PMN became very slow (Fig. 1). However, percentages of the PMN in total N tended to decrease after 15 years of rice cropping (Table 2), indicating that more N was accumulated in unavailable forms when total N reached higher levels.

3.4. C/N and H/F

The C/N ratio for the whole soil ranged from 15.8 to 8.3, decreasing significantly with increasing years of rice cropping. From Period I (0–5 years) to Period II (6–15 years), C/N ratios declined from 13.6 to

approximately 11.5 (Table 2). After 30 years of rice cropping, C/N ratios tended to be stable with a value of approximately 10 (Fig. 2). However, C/N ratios in the POM varied from 8.6 to 19.1, and was generally higher than the C/N ratios of whole soils (Table 2), indicating that POM appeared to be enriched with C relative to N. Unlike the C/N ratio in whole soil, C/N in the POM varied widely in the soils for each period of rice cropping (Fig. 2). The ratios for soils in the first 5 years were significantly higher than those in the later periods (Table 2), but the ratio was not statistically different among Period II (6–15 years), Period III (16–30 years), Period IV (31–50 years), and Period V (51–100 years).

The quality of soil organic matter, characterized by the ratio of humic acid to fulvic acid (H/F), also changed after long-term rice cropping (Fig. 2). The H/F ratio increased sharply to 0.8 in the first 15 years, and then increased gradually with increasing years of rice cropping. The elevated ratio of H/F which is an indicator of organic matter quality may be due to the wetland conditions, which are more favorable to the formation of humic acids than fulvic acids (Yu, 1994).

3.5. Changes of phosphorus and potassium

Total P in paddy soils tended to accumulate with time. The increase in total P was most obvious in the first 30 years (Fig. 3). After 50 years of rice cropping, total P was doubled, as compared with that at the initiation of rice cropping. Available P increased with time in a similar way (Fig. 4). Percentages of available P to the total P (Olsen-P/total P) also increased with time (Table 3). The highest increase in available P was found in the first 30 years (Fig. 4). Significant differences in Olsen-P, NaOH-IP, and NaOH-OP occurred

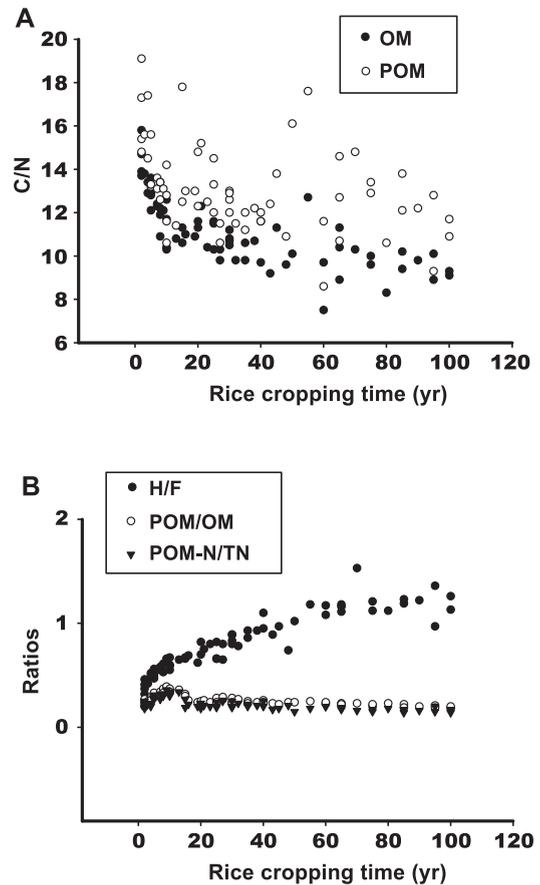


Fig. 2. Ratios of C/N (A), and H/F, POM/OM, POM-N/TN (B) in the surface soil layer (0–15 cm) as a function of rice cropping time. H, humic acid; F, fulvic acid; POM, particulate organic matter; TN, total N; OM, organic matter.

between Period I (0–5 years) and Period II (6–15 years). In addition, increases in NaOH-OP with time were more obvious than that of NaOH-IP (Table 3),

Table 3

Mean soil total phosphorus, potassium and available phosphorus in different rice cropping periods

Periods	Total P (g kg ⁻¹)	Olsen-P (mg kg ⁻¹)	Olsen-P/ Total P (%)	NaOH-IP (mg kg ⁻¹)	NaOH-OP (mg kg ⁻¹)	NaOH-OP/ NaOH-IP	Total K (g kg ⁻¹)
I (0–5 years)	0.37d	5.24c	1.43b	79.0b	43.8d	0.55d	9.78a
II (6–15 years)	0.44c	10.4b	2.38a	87.9ab	74.1c	0.85c	8.55b
III (16–30 years)	0.52ab	12.0ab	2.32a	86.5ab	89.9b	1.04b	7.09c
IV (31–50 years)	0.51b	12.7a	2.52a	87.3ab	97.0b	1.12ab	6.30c
V (51–100 years)	0.75a	13.6a	2.47a	92.5a	108a	1.18a	5.34d

NaOH-IP, NaOH extractable inorganic P; NaOH-OP, NaOH extractable organic P.

Means in each column followed by the same letter were not significantly different at $p < 0.05$.

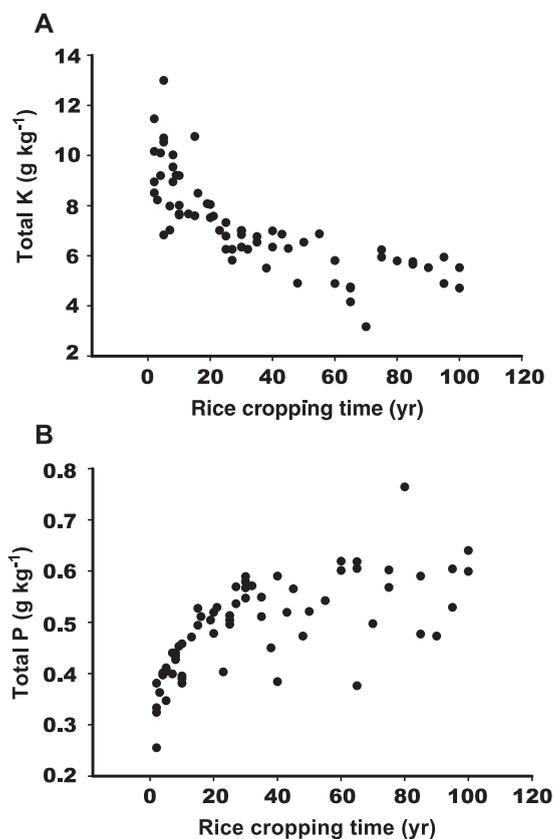


Fig. 3. Total K (A) and total P (B) in the surface soil layer (0–15 cm) as a function of rice cropping time.

evidenced by the increased ratio of NaOH-OP/NaOH-IP. This agreed with the increase in organic C. The NaOH-extractable organic P has more recently been identified as an important source of available P in tropical soils (Tiessen et al., 1992). The greater influence of long-term rice cropping on NaOH-extractable organic P suggests the importance of NaOH extractable organic P for paddy soils.

In contrast, total K in the soils decreased significantly with time. There was a significant negative correlation between total K and cultivation time with a correlation coefficient (r) of -0.76 ($p < 0.0001$). Exchangeable K in the soils also tended to decline with years of rice cropping (Table 1). Significant decreases in total K in paddy soils could be explained by both imbalanced fertilization strategy in the area and strong K leaching in the paddy soils. Due to low input of K, most irrigated rice production systems in

the region have been running under negative K balances. In the past decades, fertilization has been imbalanced in this area, with too much N (290 kg ha⁻¹) and too little K (28 kg ha⁻¹) being applied.

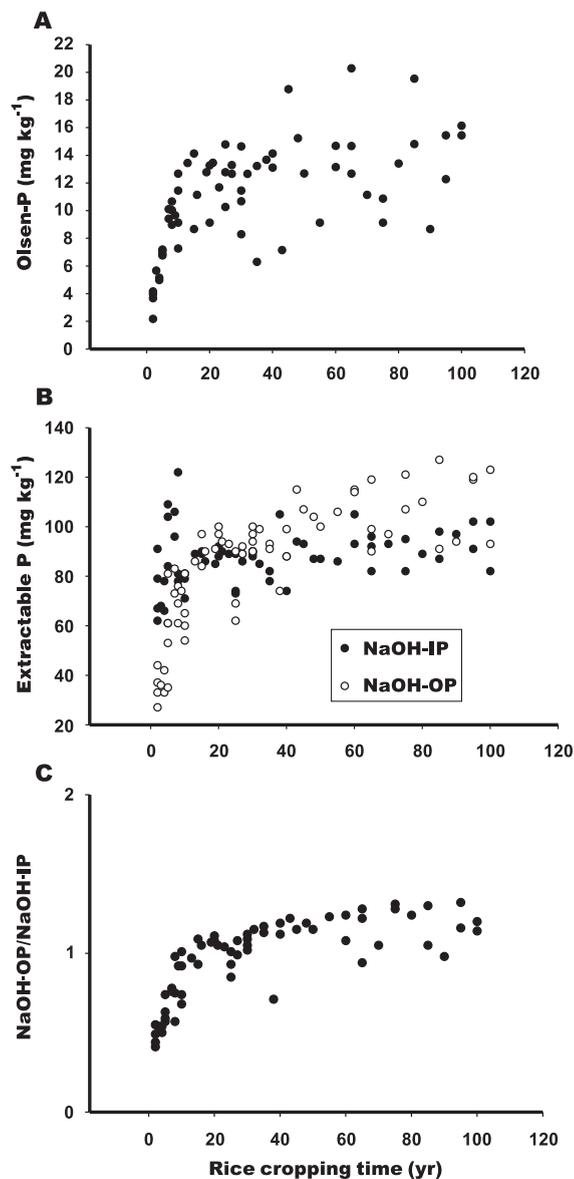


Fig. 4. Extractable phosphorus and NaOH-OP/NaOH-IP ratio in the surface soil layer (0–15 cm) as a function of rice cropping time. (A) Olsen-P; (B) NaOH-IP (NaOH extractable inorganic P) and NaOH-OP (NaOH extractable organic P); (C) ratio of NaOH-Op to NaOH-IP.

Potassium input was less than K removal by harvested rice grain and sometimes straw, which caused a net deficit in soil K. In addition, water saturation in the soils would increase K diffusion rates, and K may be lost through downward movement in soil solution or with clay. A significant positive correlation was found between total soil K and clay content ($r=0.77$, $P<0.0001$), suggesting that K tended to be leached down with clay in the rice production system. There were many studies reporting that removal of K in the crop exceeded K additions and the soil K balance was negative in rice production systems (Dobermann et al., 1998; Wihardjaka et al., 1999; Singh et al., 2002). Continuous rice cropping at a low input of K may pose a threat to the sustainability of the rice system. Increasing recycling of crop residue or application of higher levels of fertilizer K is needed for long-term sustainability to the systems.

3.6. Distribution of soil carbon, nitrogen, and phosphorus pools in soil profile

Soil organic C increased with years of rice cropping, but decreased with the depths (Fig. 5). The

difference in organic C content among six soil profiles with different years of rice cropping was the greatest in the 0–10 cm depth, followed by the 10–20 cm, and then became smaller with increasing depths. Compared to soil from the 2-year cultivations, increases in organic C and total N observed in the top 10 cm of the soil with cropping time of 5–100 years ranged from 68.3% to 265.1% and 74.5% to 378.7%, respectively. The time needed for significant change of organic C varied with the depth (Fig. 5), the change appeared first in the plow layer. For the same depths, the differences in organic C increased with the time. A comparison of organic C and N concentrations at various depths in the soils with the rice cropping time of 2, 5, 19, 48, 68, and 100 years showed evidence of continued stratification development, especially during the first 20 years. The nutrients including N and P increased rapidly in the top layer of the soil and slowly in the bottom layer, but decreases were evident for the metabolically active pools (POM) (Fig. 5). The increasing rate for the different nutrients was variable. Obvious changes in organic C appeared in the first 5 years for depths of 0–30 cm, 5–20 years for the depth 30–60 cm, 20–50 years for the depth 60–100 cm,

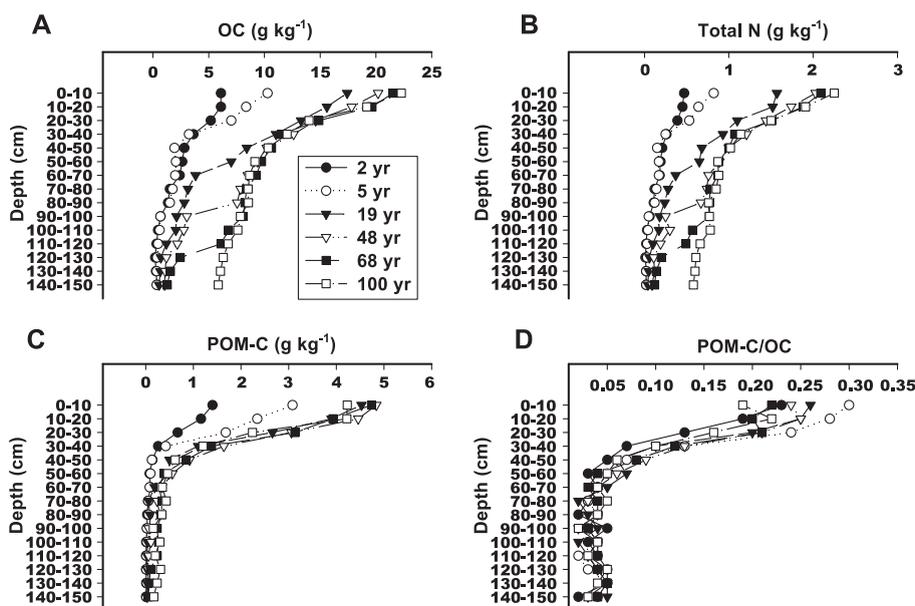


Fig. 5. Distribution of soil organic carbon and nitrogen as a function of soil depth. (A) Organic C (OC); (B) total N; (C) particulate organic matter (POM-C); (D) POM-C/OC.

and 50–70 years for the depth 100–130 cm, and 70 to 100 years for the depth 130–150 cm. These results suggest that organic C could be leached down during rice cropping season. Organic C continuously increased from topsoil to 1.5 m depth with the time, suggesting that rice cropping resulted in a steady leaching of organic C along the soil profile. Similar results were obtained for total N (Fig. 6). The results suggest that large consumption of chemical fertilizer N could cause N leaching and may pose potential impacts on the environment.

POM-N had a different pattern in the profiles compared with total organic C and total N. Significant differences in the POM-C among soil profiles with different years of rice cropping was only found in depths of 0–40 cm with no obvious difference below 50 cm. These results indicate that the organic C is leached down in the form of dissolved organic matter, which is evidenced by the fact that the proportion of

POM-C in total organic C decreased sharply with depth. A pot experiment by Maie et al. (1997) indicated that dissolved organic C (DOC) could be leached from the submerged plow layer of rice paddies during the cultivation period and accumulated in the subsoil. Total amount of the DOC leached throughout a growth period of rice plant could reach 0.5% of total C in the plow layer. In addition, clay movement downward could also increase migration of organic matter along the soil profiles, because organic matter could be complexed with clay.

Phosphorus concentrations increased gradually with the time and depth. After 68–100 years of rice cropping, P concentrations in the surface soil (0–30 cm) doubled, as compared to soils at the initiation of rice cropping. In addition, P concentrations in the 30–100 cm depth also increased significantly. With increasing years of rice cropping, Olsen-P increased first in the surface horizon and then in the subsurface

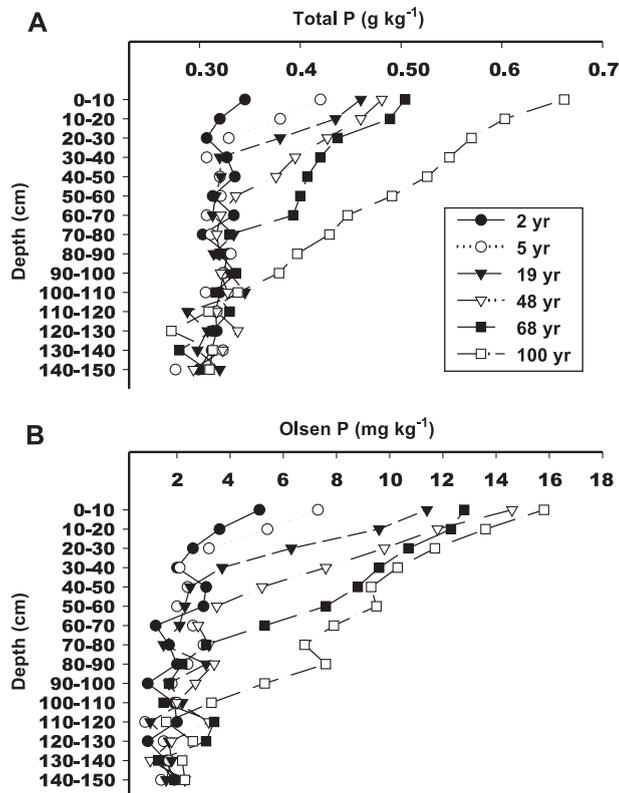


Fig. 6. Distribution of soil total P (A) and Olsen-P (B) as a function of soil depth.

soil. The increase in available P with depth indicates that rice management and fertilization enhanced leaching of P in the soil profile in rice production systems, and the effect was up to 100 cm depth. Increased solution P concentration after flooding may increase the potential for P movement downward due to leaching compared to non-flooded soils (Xiao, 1988). Mechanical disturbance (plowing), and frequent irrigation and drainage during the rice growth season could also enhance the downward movement of P.

The positive effects of long-term rice cropping on accumulations of soil organic C and nutrients are clearly demonstrated in Fig. 7. Total soil organic C in the whole 1.5 m depth profile was high, averaging 4.85, 5.74, 12.92, 17.52, 20.67 and 22.51 kg m⁻² for 2, 5, 19, 48, 68 and 100 years of continuous rice, respectively. 22.8–27.5% of the soil organic C was in the 0–20 cm depth, with the highest value in the 2 years rice cropping field and the lowest in the 100 years rice cropping field, this meant that the percentage of organic C storage for the subsoil in the whole 1.5 m soil profile increased with time. Organic C and total N were significantly different among soil profiles with different years of rice cropping, storage of organic C and total N at the depths of 0–20 cm and 20–50 cm increased sharply in the first 20 years, and then remained relatively stable in the next 30 years. In contrast, the storage of organic C and total N at the depth of 50–150 cm increased gradually with time, and they continued to increase even after 70 years of rice cropping. Total P increased slowly with time. These results showed a great increase in soil organic C below the plow layer with long-term rice cropping. Therefore, measurement of rice cropping effects on soil organic C and total N only in the plow layer would significantly underestimate the total increase in soil organic C and total N in the soil profile. These results suggest that considerable amounts of the added N, C, and P have accumulated in the soils and rice cultivation system seems to have potential in conserving N and C in the soils.

3.7. Grain yield

Based on an investigation in 1998, total grain yield of early and late rice increased exponentially with increasing time of rice cropping (Fig. 8). The average

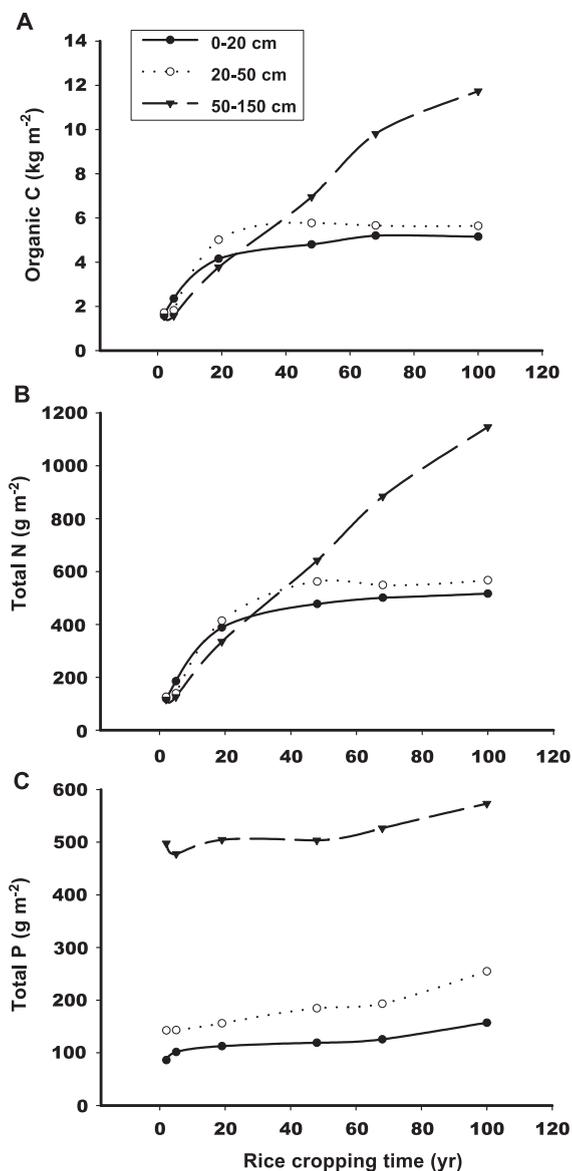


Fig. 7. Changes in soil organic C (A), total N (B) and total P (C) storages in different depths as a function of rice cropping time.

yields were 6.29, 9.16, 11.19, 12.34, and 12.55 Mg ha⁻¹ for the fields of Periods I, II, III, IV, and V, respectively. A very significant increase of the yield was found in the first 15 years. During Period III, the yield increase rate was slowed down and leveled off thereafter. Recently, it has been concerned that rice production in some old fields has started to decline

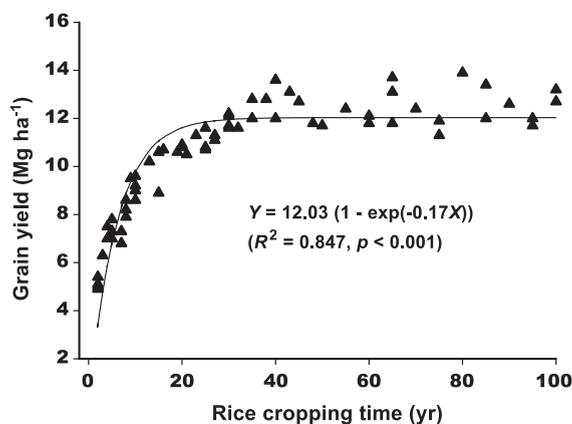


Fig. 8. Relationship between grain yield in 1998 and rice cropping time.

(Zhejiang Statistical Bureau, 2000). The decreased rice production may partly be due to imbalanced fertilization by high N and low K.

4. Conclusions

Long-term rice cropping affected the soil organic C, and total N, P, and K in irrigated paddy fields that were derived from red soils. Significant increases in organic C content, total N, and P pools in the plow layer were found in the first 30–40 years of rice cropping, accompanied with increases in available P and potential mineralizable N, exchangeable Ca, Mg, Na, base saturation, and water-stable aggregates, and decreases in clay content. Long-term rice cropping also increased soil C, N, and P in the subsurface soils. The result suggested that organic C, N, and P accumulated significantly in the soil profile under rice cropping systems. Conversion of red soil upland to irrigated rice fields has great potential to increase soil C, N, and P pools. However, K in the plow layer tended to decrease with time due to imbalanced fertilization by high N and low K, and strong leaching. Results also show that current fertilizer recommendations are inadequate for maintaining soil K levels, and rice production may not be sustainable without increasing K inputs to maintain adequate soil K at proper levels. Over the long run, both depletion and excessive accumulation of nutrients have negative effects on soil quality and environment.

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