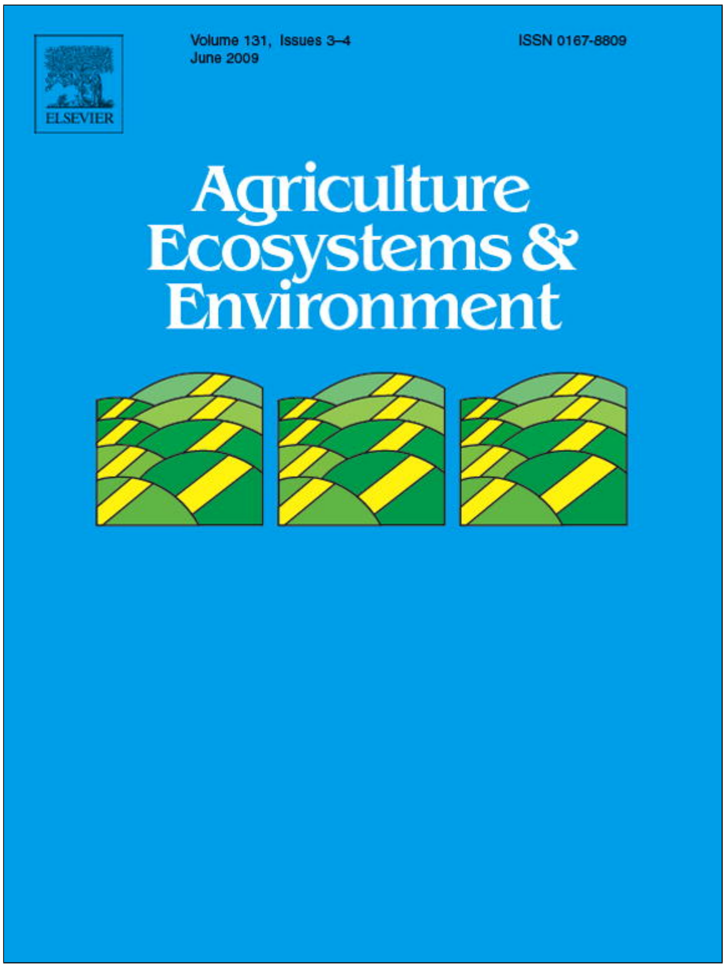
Volume 131, Issues 3–4
June 2009
ISSN 0167-8809
ELSEVIER
Agriculture
Ecosystems &
Environment

Agriculture, Ecosystems and Environment 131 (2009) 274–280

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Combined inorganic/organic fertilization enhances N efficiency and increases rice productivity through organic carbon accumulation in a rice paddy from the Tai Lake region, China

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ARTICLE INFO

Article history:
Received 20 September 2008
Received in revised form 29 January 2009
Accepted 29 January 2009
Available online 10 March 2009

Keywords:
Rice paddy
Rice production
Soil organic carbon
N efficiency
Greenhouse gas offsetting
Combined fertilization
Soil microbial activity

ABSTRACT

The effect of fertilization practices on crop productivity and C storage of cropland soils has been a key focus of research into sustainable agriculture and global change. We present results from a long-term fertilization trial in a rice paddy in the Tai Lake region, China and report variation of rice yields and N efficiency with organic carbon accumulation under different fertilization regimes. The fertilization treatments were no fertilizer application (NF), application of chemical fertilizers only (CF), combined application of chemical fertilizers and pig manure (CFM), and straw return (CFS), respectively since 1987. The rice paddy had been consistently cultivated with double cropping of rice (*Oryza sativa*) and rape (*Brassica campestris*) under minimum tillage. The yields of rice grain and rape seeds were recorded each year. Topsoil samples from 0 to 5 cm and 5 to 15 cm were collected after rape harvest in 2005 and soil organic carbon (SOC) contents and properties of microbial activity were determined. Significant differences in average rice yield, but not rape yield, were observed between the fertilization treatments. A higher and more stable yield of rice was found under CFM and CFS than under CF. Since 1987, there has been a prominent topsoil C accumulation in a range of 0.1–0.4 t ha^{-1} yr^{-1}, being greater under CFS and CFM than under CF. Comparing between the fertilized plots, grain productivity and C accumulation was enhanced by 21% and 24%, and 72% and 103% under CFM and CFS compared to CF, respectively. Increased rice productivity was coincident with an increased organic C accumulation rate under fertilization. The coupled effect of increased rice yield and C accumulation may be attributable to the enhanced microbial activity, which was found much higher under combined fertilization. N use efficiency was higher under combined fertilization (by 12.6% and 39.0% for CFM and CFS, respectively) compared to inorganic-only fertilization, meaning that less inorganic N fertilizer would be required for the same level of production, thereby potentially saving C emissions from fertilizer manufacture. This study suggests a win–win effect of combined inorganic/organic fertilization on soil organic carbon accumulation and crop productivity in rice fields through increasing N efficiency possibly by enhanced microbial activity. Well-managed, combined organic/inorganic fertilization could both enhance C storage in soils, and reduce emissions from N fertilizer use, while contributing to high crop productivity in agriculture.

1. Introduction

Enhancement of soil organic carbon (SOC) in cropland soils is considered as an option for offsetting the increasing atmospheric CO_2 concentration, while improving soil fertility for crop production (Smith, 2004). SOC storage and the dynamics of C stock change in croplands have become an important issue in evaluating the impact of agricultural management on global climate change (Lal, 2003; Smith et al., 2008). China has long strived to ensure food security through sustainable cereal productivity (Brown, 1995), which has been largely supported by rice paddies with high grain productivity. As a unique type of anthropogenic soil in China, paddy soils contain about 9 t ha^{-1} on average more topsoil SOC than dry cropland soils (Pan et al., 2003a; Pan and Zhao, 2005). Enhancement of topsoil SOC has been extensively observed in the rice paddy area of South China over the last 20 years, particularly in the Tai Lake region, Jiangsu (Pan et al., 2003a,b; Huang and Sun, 2006; Li and Wu, 2006; Tang et al., 2006). Good management of

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doi:10.1016/j.agee.2009.01.020

Table 1
Basic properties of the studied soil (sampled and measured in 1987).

Depth (cm)	SOC (g kg^{-1})	Total N (g kg^{-1})	pH (H_2O)	Clay (<2 (m, g kg^{-1})	CEC (cmol kg^{-1})
0–5	16.40	1.72	5.60	249.30	20.20
5–15	16.00	1.68	6.00	279.70	20.90

Table 2
Basic properties of soil (0–15 cm) under different fertilization treatments (sampled and measured after rice harvest in 2005).

Treatment	Bulk density (g cm^{-3})	TOC (g kg^{-1})	Total N (g kg^{-1})	pH (H_2O)	N fertilized* (kg N ha^{-1} yr^{-1})
NF	1.10	16.18	1.65	6.13	0
CF	1.18	17.43	1.78	5.93	427.50
CFM	1.14	19.38	1.97	5.74	528.30
CFS	1.18	19.24	1.84	5.88	452.25

* N content of straw and pig manure added, were on average 0.55% and 0.60%, respectively.

China's rice paddies is considered crucial, not only for sustaining grain production, but also for enhancing the climate change mitigation capacity of agriculture (Pan, 2008). However, it is not clear if SOC enhancement in rice paddies could be coupled with improved grain productivity, or how different fertilization practices affect SOC and grain productivity in paddy soils. Using data from long-term experiments, Zhang et al., 2005, Zhou et al. (2006) and Zheng et al. (2006, 2007) demonstrated that the content and pool distribution of topsoil SOC, and production of GHGs from rice paddies varied greatly with different fertilization practices. In a recent review paper, Pan (2008) argued that croplands in China may play a significant role in climate change mitigation in agriculture. This raises the question of how productivity in the rice sector can be maintained while minimizing greenhouse gas emissions, as China is facing great challenges, both for food supply and for greenhouse gas mitigation.

Using a long-term fertilization trial from the Tai Lake region, China as a case study, variation of topsoil SOC storage, rice productivity and soil microbial activity under different fertilization regimes was examined to determine the effect of fertilization practices on both grain production and SOC enhancement. The purpose of this work is to offer information for understanding the role of cropland management in meeting the challenge of increasing grain production and enhancing resilience adaptation and mitigation of climate change in China's agriculture.

2. Materials and methods

2.1. Soil and site

The rice paddy that we studied is located in Jinjiaba Township, Wujiang Municipality, Jiangsu Province, China (31°05′900″N and 120°46′924″E). Rice cultivation in the area had been developed for several thousands of years (Xu, 2001). Derived from lucstrine deposit, the soil was a typical high-yielding paddy soil classified as a Ferric-accumulic Stagnic Anthrosols (Gong, 1999) and an entic Halpudept (Soil Survey Staff, 1994). A subtropical monsoon climate prevailed in the area with mean annual temperature and precipitation of 22 °C and 1100 mm, respectively, between 1980 and 1996.

2.2. Fertilization treatments

A long-term fertilization trial was initiated on a rice paddy in 1987. The fertilization treatments, described in detail by Xu et al. (1999), were designed as follows: no fertilizer application (NF), chemical fertilizer only (CF), chemical fertilizer plus pig manure (CFM), and chemical fertilizer plus rice straw return (CFS). The annual application of chemical fertilizers was 427.5 kg N, 45 kg P_2O_5 and 54 kg K_2O ha^{-1} consistently in the fertilized plots. For N, 55% was applied in the rice season and the other 45% in the rape season. Potassium and phosphorus fertilizers were supplied only in the rape season. However, pig manure and rice straw were applied at fresh weight of 8400 kg and of 4500 kg ha^{-1}, respectively for the CFM and CFS plots. Pig manure or rice straw was incorporated into the soil after rice harvesting. The double cropping of rice (*Oryza sativa*) (late spring to autumn) and rape (*Brassica campestris*) (late autumn to next late spring) had been rotated and minimum tillage after the rice harvest had been operated consistently since the initiation of the experiment in 1987. The treatment plots were arranged in a randomized block design and conducted in triplicate. Each plot was 66.7 m^2 in area and was managed with separated irrigation and drainage. The basic soil properties before the trial in 1987, and under the different fertilization regimes in 2005, are shown in Tables 1 and 2.

2.3. Soil sampling and analysis

For the precise assessment of topsoil SOC, seven samples of 0–5 cm and 5–15 cm were collected respectively by a grid sampling procedure from each plot after the rape harvest in 2005. Soil sampling was done with Eijkelkamp soil core sampler. The samples were sealed in plastic bags and shipped to the laboratory within 2 days. Root detritus was removed and the soil air-dried and ground to pass a 2 mm sieve prior to analysis. A portion of soil was further ground to pass a 0.15 mm sieve for C and N analysis by the wet digestion method with potassium dichromate and by semi-micro Kjeldahl method (Lu, 2000). Soil bulk density was also measured when sampling in the field using cylinders of 100 cm^3 in volume, in 10 random replicates.

Samples for soil microbial activity measurement were taken after rice harvest in 2005. Microbial Biomass C and N measurement was done using the fumigation-extraction procedure described by Vance et al. (1987).

2.4. Estimation of C input and accumulation in topsoil

2.4.1. C input to soil

Estimation of C input from crop residue and organic fertilizers was done following He and Ni (1996) and Song (1995) for SOM budgeting under fertilization in an adjacent area. The C input through residue (C_r, t ha^{-1} yr^{-1}) of root and shoot in soils was calculated by the following equation:

$$C_r = Y \times P \times C_p \times D \quad (1)$$

where Y is the grain yield (t ha^{-1} yr^{-1}) of rice or rape seed, P is the partitioning factor of root biomass (0.25 for rice and 0.20 for rape), C_p is the mean C content of the plant derived material (37% for rape and rice crops on average), D is the transformation factor of residue C to soil C after decaying (0.40 on average).

C input through organic amendments (C_f, t ha^{-1} yr^{-1}) was calculated using following equation:

$$C_f = Q_f \times C_f \times D_f \quad (2)$$

where Q_f is the total amount of organic amendments applied (t (dry matter) ha^{-1} yr^{-1}), C_f is the mean C content of the organic amendments (38% for pig manure in dry matter), D_f is the transformation factor of fertilized C to soil C after decaying (0.25 for pig manure).

2.4.2. Organic C accumulation in topsoil

Storage of the topsoil SOC was calculated with the following equation (Pan et al., 2003a):

$$D_{oc}\,(\text{Topsoil}) = \text{SOC} \times \gamma \times H \times 10^{-1} \quad (3)$$

where D_{oc} is the SOC storage in t C ha^{-1}, SOC is the mean SOC content in g kg^{-1}, γ is the measured bulk density in g cm^{-3} and H is the topsoil thickness, being 15 cm in this case.

The observed annual C accumulation rate was calculated by the difference in C storage under a given treatment between of the measured year and of the initial in 1987, divided by the duration years.

2.5. Estimation of N input and calculation of N efficiency

The chemical N input was same for all the fertilized plots. N input from straw return and manure amendments was calculated using mean N content of 0.55% for rice straw and 0.60% for dry pig manure as reported by He and Ni (1996) and Song (1995).

N efficiency for rice was calculated using mean rice yield divided by estimated N input according to the N allocation to rice with different fertilization treatments.

2.6. Statistical analyses

Data analysis was conducted using Microsoft Excel 2003. All values were expressed as the mean plus and minus one standard deviation. The difference between the fertilization treatments was tested using one-way ANOVA. The significance of the difference was defined according to statistical convention at $p < 0.05$.

3. Results

3.1. Variation of rice productivity with fertilization treatments

The variation of rice and rape yield with fertilization treatment became consistent after the 6th year of the experiment (Zhang et al., 2004). We therefore present data of mean rice and rape seed yields since the 6th year in Fig. 1. There was no wide difference in rape seed yield between the different fertilizer treatments, ranging from 2.2 to 2.6 t ha^{-1} yr^{-1} in the fertilized plots, despite of a much lower yield at 0.37 t ha^{-1} yr^{-1} under NF. This may be due to the relative small grain yield and phosphorus and potassium fertilizers were not applied for rape. However, there was a greater difference between the fertilization treatments in rice grain yield. The average rice yield reached 8.00 and 8.19 t ha^{-1} yr^{-1} under CFS, CFM, respectively, compared to 6.43 t ha^{-1} yr^{-1} under CF treatments, although a low yield of 3.65 t ha^{-1} yr^{-1} was found under NF. This demonstrates an impact of fertilization practice on rice production in the rice paddy. The annual total grain production was increased by 21% and 24% under CFM and CFS compared to under CF. Meanwhile, N efficiency varied dramatically with the fertilization treatments (see below).

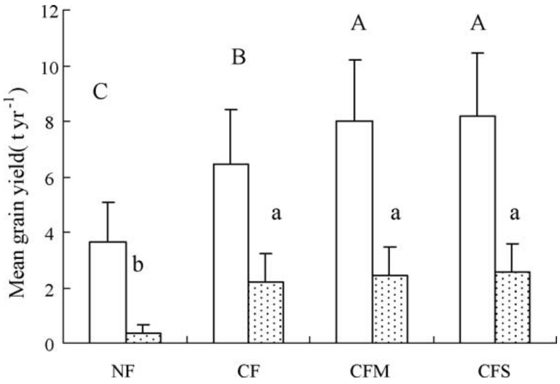

Fig. 1. Mean and standard deviation of grain yield under different fertilization regimes (Blank, rice; Shaded, rape seed). Different characters mean significant difference between the treatments at $p < 0.05$. NF, no fertilization; CF, inorganic fertilizers only; CFM, inorganic fertilizer with manure; CFS, inorganic fertilizers with straw return).

3.2. Accumulation of organic carbon in topsoil

Topsoil SOC measurements for each plot after fertilization for 17 years are given in Table 3. A significant increase in SOC was found under all treatments compared to the initial measurements in 1987. It appeared that combined application of chemical and organic fertilizers greatly significantly increased the SOC content. SOC was enhanced by 1.79, 1.92, 4.12 and 3.64 g kg^{-1} at 0–5 cm depth under NF, CF, CFM and CFS, respectively. Comparatively, SOC in the 5–15 cm layer was increased by 2.81 and 2.84 g kg^{-1} under CFM and CFS, respectively, in contrast to an increase of 0.99 g kg^{-1} under CF and a decline by 0.82 g kg^{-1} under NF. The decrease at 5–15 cm under NF could be attributed to increased mineralization for nutrient supply, or to less input from crop biomass.

Table 3 shows the calculated topsoil (0–15 cm) SOC storage under different fertilization treatments. Ranging from 30.9 to 34.1 t C ha^{-1}, topsoil SOC storage under fertilizer treatments was significantly increased compared to that under NF. Topsoil C

Table 3
SOC content (g kg^{-1}) and storage (t C ha^{-1}), and C input and C accumulation (t C ha^{-1} yr^{-1}) under different fertilization treatments (sampled after rape harvest and measured in 2005).

	Depth (cm)	NF	CF	CFM	CFS
Content	0–5	18.19 ± 1.55b	18.32 ± 1.07b	20.52 ± 0.54a	20.04 ± 0.96a
	5–15	15.18 ± 1.44c	16.99 ± 0.95b	18.81 ± 0.51a	18.84 ± 0.92a
Storage	0–15	27.90 ± 2.23c	30.94 ± 1.75b	33.11 ± 0.89a	34.05 ± 1.65a
Estimated C input		0.15 ± 0.06d	0.30 ± 0.07c	0.54 ± 0.11ab	0.55 ± 0.11a
Observed C accumulation		0.15 ± 0.07d	0.33 ± 0.03c	0.42 ± 0.02b	0.51 ± 0.03a

Different characters in a single row indicates significant difference at $p < 0.05$.

Table 4
Microbial biomass C, N and DGGE diversity of the topsoil (0–15 cm) under different fertilization treatments (sampled and measured after rice harvest in 2005).

	NF	CF	CFM	CFS
SMBC (mg kg^{-1})	114.99 ± 13.72d	129.02 ± 12.66c	145.33 ± 15.48b	149.45 ± 31.88ab
SMBN (mg kg^{-1})	4.45 ± 0.00d	6.83 ± 0.58c	10.19 ± 0.68b	13.16 ± 0.95a
Microbial gene diversity[a]	0.63 ± 0.11b	0.72 ± 0.23b	0.95 ± 0.20a	1.03 ± 0.19a

Data presented in mean ± standard deviation. Different characters in a single row indicate significant difference between treatments at $p < 0.05$.
[a] Data from Zhang et al. (2004a,b,c) analyzed with rational method of polymer chain reaction and denaturing gradient gel electrophoresis (PCR-DGGE).

storage was over 10% higher under both CFS and CFM treatments than under CF, though the differences in the C storage of whole soil (0–100 cm) between fertilizer treatments were not significant due to the bigger variability of profile samples (Zhou et al., 2006). The observed topsoil SOC accumulation rates ranged from 0.15 t C ha^{-1} yr^{-1} to 0.51 ha^{-1} yr^{-1}, close to the estimated C input. The combined inorganic fertilizers/organic amendments treatment (CFM and CFS) exerted a profound effect on the SOC accumulation rate, with the accumulation rate increased significantly (by ~50%) under CFM and CFS, compared to CF (Table 3). The topsoil storage and accumulation rate of SOC reported here is within the range reported in our previous survey of rice paddies in a similar region (Zhang et al., 2004a,b,c).

3.3. N efficiency and soil microbial biomass C and N

The estimated N input from fertilizers is listed in Table 2. There had been no much difference in amount of fertilized N between under different fertilizer treatments. However, the calculated mean fertilizer N efficiency (kg grain per kg of fertilized N) for rice varied in a wide range of 11.8–18.2 with the following order: CFS > CFM > CF (data incorporated in Fig. 4).

Table 4 shows soil microbial activity of the topsoil sampled after the rice harvest in 2005. Microbial biomass C ranged from 115.8 mg kg^{-1} under NF to 150 mg kg^{-1} under CFS, although this is smaller than those reported for rice paddies from the red soil region by Liu et al. (2006). There was a very significant difference in extractable microbial biomass C, N, and in the microbial quotients between the different fertilization treatments, being much higher under CFS and CFM than CF among the fertilized plots, with NF have the lowest levels. The difference was greater in microbial biomass N than in microbial biomass C.

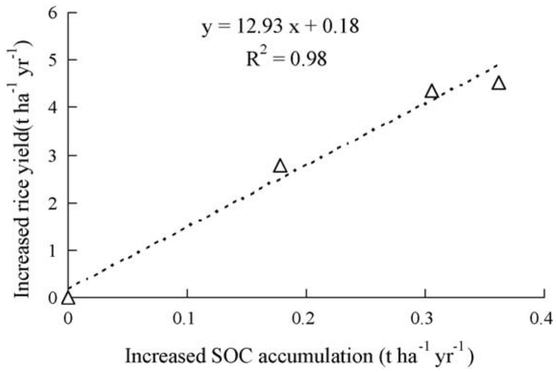

Fig. 2. Correlation of mean increased rice yield with increased mean SOC accumulation under fertilization compared to no fertilization. CF, inorganic fertilizers only; CFM, inorganic fertilizer with manure; CFS, inorganic fertilizers with straw return.

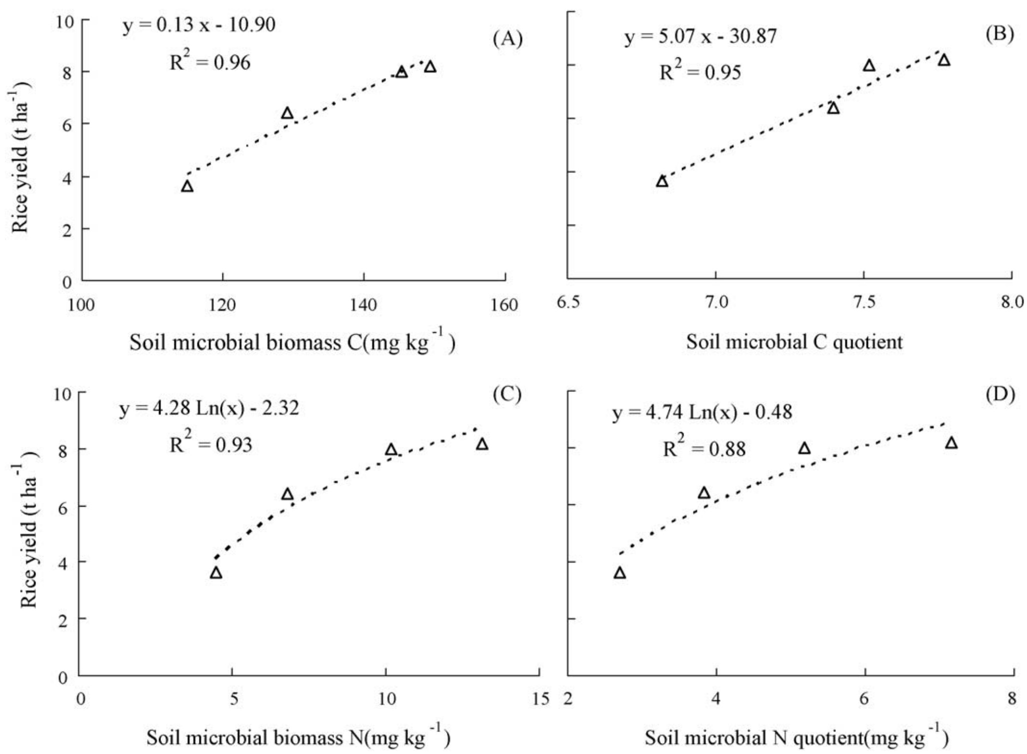

Fig. 3. Correlation of mean rice yield with soil microbial properties under different fertilization treatments (A and B: with microbial biomass C and the quotient; C and D: with microbial biomass N and the quotient, respectively).

4. Discussion

4.1. Rice productivity and SOC accumulation under different fertilization regimes

While the effect of combined inorganic/organic fertilizers (e.g., CFM and CFS) on crop yield and SOC content in rice paddies had been frequently studied (He and Ni, 1996; Wang et al., 2004), the coupling of crop production with C accumulation has not previously been discussed. Here, after 17 years of a long-term trial, there were large differences in crop productivity between the different fertilization regimes. Total grain production remained consistently higher under CFM and CFS, though changes in rape seed production were smaller (Zhang et al., 2004a,b,c). Accumulation of topsoil SOC differed between fertilization treatments with greater increases in treatments receiving higher organic matter amendments (Table 3). Regression analysis shows that the mean increase in rice yield is linearly correlated with the increased SOC accumulation rate under fertilization compared to no fertilization (Fig. 2). While rice yield variability between treatments has been found to related to the microbial DGGE diversity in previous studies of molecular microbiology (Zhang et al., 2004a,b,c), rice yield in this study is shown to be positively related linearly (C) and logarithmically (N) to soil microbial biomass C and N, and the respective microbial C and N quotients (Fig. 3). Reduced rice yield with decreased microbial biomass C and N had been reported by Yao et al. (2000) under changing land use history, and by Wang et al. (2004) under long-term unbalanced fertilization in similar rice paddies in an adjacent area. Thus, enhanced rice production under combined organic/mineral fertilizers in this study could be accounted for by the improvement of microbial activity, as characterized by the increased microbial biomass C and N quotient.

The effect of soil C sequestration on crop productivity and hence on world food security has been stressed by Lal (2004). The data presented in this case study support the role of SOM in sustaining cropland cereal productivity, at least for rice, with a higher yield in the combined organic/inorganic fertilizer treatment compared to the inorganic-only fertilizer treatment (despite similar N additions). This suggests that enhancement of SOC in croplands may help to enhance the cereals production, as well as increasing soil carbon sequestration (Pan and Zhao, 2005). Moreover, taking into account the SOC accumulation and decrease of SOM decomposition rate under the combined organic/inorganic treatments (CFM and CFS) (Zheng et al., 2006, 2007), combined fertilization of inorganic fertilizers with organic amendments may offer win–win options for sustainable rice production.

4.2. N efficiency and GHG balance of combined organic/inorganic fertilizer treatments

N availability in natural grass or forest ecosystems has major effects on soil microbial respiration and SOC decomposition (Hu et al., 2001; Nadelhoffer et al., 1998; Reay et al., 2007; Zhang et al., 2007). While soil N accumulation is generally considered to favour C sequestration in agricultural soils (Christopher and Lal, 2007; Pan et al., 2003b), neither SOC accumulation (Zhou et al., 2006) nor soil respiration and CO_2 flux (Chen et al., 2005; Zheng et al., 2006, 2007) was observed to vary with N status under the different fertilization treatments. Nevertheless, N use efficiency for rice yields varied greatly between fertilization treatments. As shown in Fig. 1, the crop yield did not vary with the N input under different treatments. Compared to NF, mean use efficiency of fertilized N for rice yield was estimated as 11.8, 15.0 and 18.2 t rice grain t^{-1} N fertilizer, respectively, under CF, CFM and CFS. The N use efficiency was increased by 27% under CFM and 54% under CFS compared to under CF. The effect of straw amendments was almost double that of manure. This coincides with the trend in microbial N between fertilization treatments (Fig. 4). Yao et al. (1999) attributed higher N use efficiency and crop growth under combined fertilization to the increased microbial quotient in a fertilizer experiment using a red-earth derived rice soil paddy. Liu et al. (2006) found higher N use efficiency in high-yielding rice paddies and related this to a increased microbial quotient under well-managed fertilization

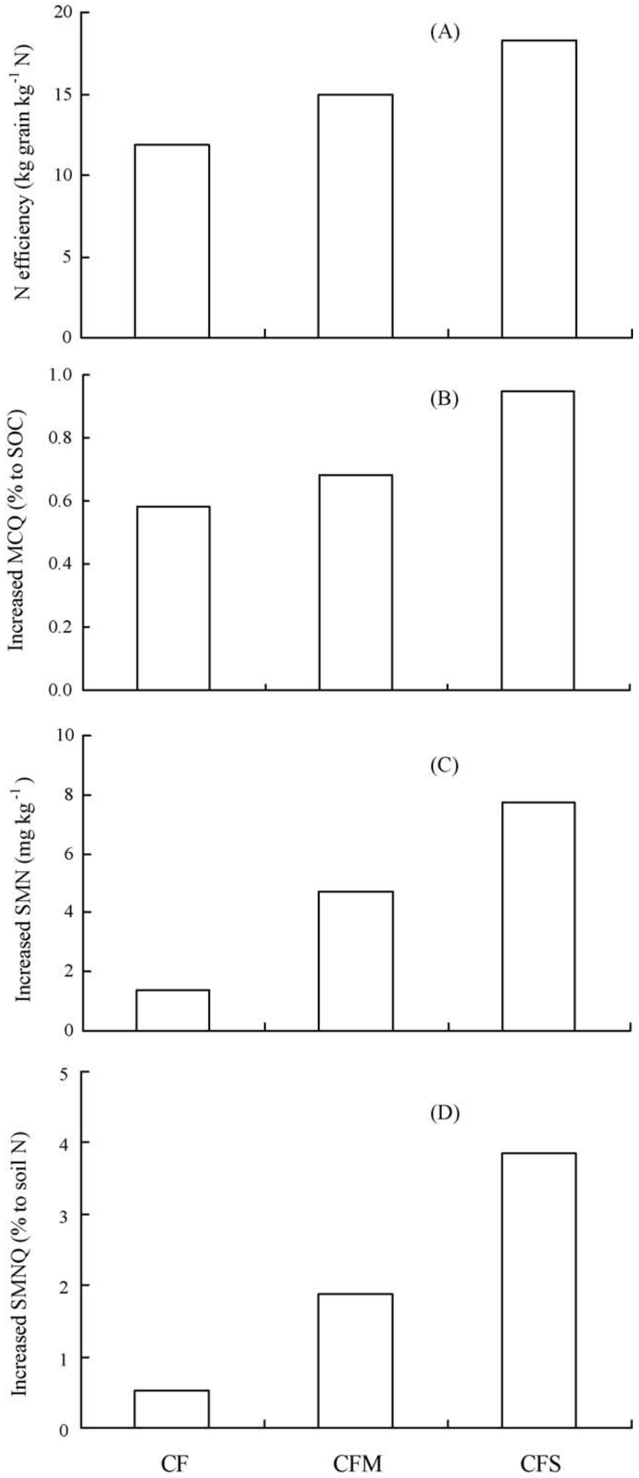

Fig. 4. Variation of fertilizer N use efficiency (A) for rice (kg grain per kg N), increased microbial C quotient (B) (% to SOC), increased microbial N (C) (mg kg^{-1}) and increased microbial N quotient (D) (% to soil N) under fertilization compared to under no fertilization. CF, inorganic fertilizers only; CFM, inorganic fertilizer with manure; CFS, inorganic fertilizers with straw return.

practices from the Dongting Lake region, China. The improvement of soil microbial activity, therefore, may be responsible for the increased N availability, with higher microbial N and a higher microbial biomass N quotient.

The N efficiency for grain production under combined organic/inorganic treatments is higher than the average N use efficiency in China's agriculture of 7.5 kg kg N^{-1}, as reported by Zhu (1997). N use efficiency in high production paddy soils from the same region has been shown in a fertilizer field trial to be as much as 9.3 kg kg N^{-1} under a balanced fertilization scheme, compared to fertilization with excess N and P (Pan et al., 2003a,b). In this study, the N use efficiency and soil C accumulation was 1.5–1.8 times, and 1.6 times higher respectively under combined fertilization compared to inorganic fertilization only. Using mean rice yield and the total N input, on average 85 kg of fertilizer N is consumed for production of 1 t of rice under CF, compared to 67 and 55 kg of N under CFM and CFS. Total rice production and total N fertilizer consumption of China reached 200 and 6 Mt respectively at the end of 20th Century (Peng et al., 2002). As N fertilizer use could be reduced under combined organic/inorganic fertilization by ~35% for a same yield compared to CF, one can calculate that ~2 Mt yr^{-1} of inorganic N fertilizer could potentially be saved by using combined organic/inorganic fertilization practices in rice agriculture. Production of N fertilizer per ton consumed 0.88 t C t^{-1} N^{-1} on average in U.S.A. (West and Marland, 2002) and 1.74 t C in China (Lu et al., 2008) as coal had been used with ammonium synthesis in China's chemical fertilizer industry. Therefore, the potential reduction in N fertilizer consumption may offset 1.7–3.5 Mt C emission per year in China's agriculture. Thus, combined organic/inorganic fertilization in croplands not only enhances soil C storage, but has the potential to significantly reduce C emissions from fertilizer manufacture through improved N use efficiency also.

5. Conclusions

This study shows that combined organic/inorganic fertilization improves microbial activity and enhances N efficiency, while increasing grain production and C accumulation in the rice paddies. Combined organic/inorganic fertilization may also reduce C emissions from fertilizer manufacture through improved N use efficiency. The full greenhouse gas balance (including the impact on nitrous oxide emissions) of combined organic/inorganic fertilization is yet to be quantified, but for every parameter measured here (productivity, soil C storage, improved N efficiency/reduced demand for inorganic fertilizer), it appears to offer multiple win opportunities for food security and reduction of net GHG emissions.

Acknowledgments

This study was partially supported by the Natural Science Foundation of China (NSFC) under grants 40830528 and 407100190002. Pete Smith is a Royal Society-Wolfson Research Merit Award and a UK BBSRC China Partnership Award holder.

References

Brown, J.L., 1995. Who Will Feed China? Wake-up Call for a Small Planet. W.W. Norton & Company, New York.

Chen, Y., Wu, C.Y., Shui, J.G., Wang, J.Y., 2005. Emission and fixation of CO_2 from soil system and influenced by long-term application of organic manure in paddy soils. Sci. Agric. Sin. 38 (12), 2468–2473 (in Chinese).

Christopher, S.F., Lal, R., 2007. Nitrogen management affects carbon sequestration in North American croplands. Crit. Rev. Plant Sci. 26, 45–64.

Gong, Z.T., 1999. Chinese Soil Taxonomy: Theory Approaches and Application. China Science Press, Beijing, 160–165 (in Chinese).

He, N.Z., Ni, W.Z., 1996. Fluctuation and balance of organic carbon in high yielding paddy soil with wheat-rice cropping system as affected by different fertilizer management. Plant Nutr. Fertil. Sci. 2 (4), 315–321 (in Chinese).

Hu, S., Chapin, F.S., Firestone, M.K., Field, C.B., Chiariello, N.R., 2001. Nitrogen limitation of microbial decomposition in a grassland under elevated CO_2. Nature 409, 188–191.

Huang, Y., Sun, W.J., 2006. Tendency of SOC change in cropland soils of China over the last 20 years. Chin. Sci. Bull. 51 (15), 1785–1803.

Lal, R., 2003. Global potential of soil carbon sequestration to mitigate the greenhouse effect. Crit. Rev. Plant Sci. 22 (2), 151–184.

Lal, R., 2004. Soil C sequestration impacts on global climatic change and food security. Science 304, 1623–1627.

Li, Z.P., Wu, D.F., 2006. Organic carbon content at a steady state and the potential of C sequestration of paddy soils in subtropical China. Acta Pedol. Sin. 43 (1), 46–52 (in Chinese).

Liu, S.L., Su, Y.R., Huang, D.Y., Xiao, A.H., Wu, J.S., 2006. Response of Cmic-to-Corg to land use and fertilization in subtropical region of China. Sci. Agric. Sin. 39 (7), 1411–1418 (in Chinese).

Lu, R.K., 2000. Methods of Soil and Agro-chemical Analysis. China Agric. Sci. Tech. Press, Beijing (in Chinese).

Lu, F., Wang, X.K., Han, B., Ouyang, Z.Y., Duan, X.N., Zheng, H., 2008. Assessment on the availability of nitrogen fertilization in improving carbon sequestration potential of China's cropland soil. Chin. J. Appl. Ecol. 19 (10), 2239–2250 (in Chinese).

Nadelhoffer, K.J., Emmett, B.A., Gundersen, P., Kjonaas, O.J., Koopmans, C.J., Schleppi, P., 1998. Nitrogen deposition makes a minor contribution to carbon sequestration in temperate forests. Nature 398 (11), 145–148.

Pan, G.X., 2008. Soil organic carbon stock, dynamics and climate change mitigation of China. Adv. Climate Change Res. 4 (5), 277–284 (in Chinese).

Pan, G.X., Li, L.Q., Wu, L.S., Zhang, X.H., 2003a. Storage and sequestration potential of topsoil organic carbon in China's paddy soils. Global Change Biol. 10, 79–92.

Pan, G.X., Li, L.Q., Zhang, X.H., Dai, J.Y., Zhou, Y.C., Zhang, P.J., 2003b. Soil organic carbon storage of China and the sequestration dynamics in agricultural lands. Adv. Earth Sci. 18 (4), 609–618 (in Chinese).

Pan, G.X., Zhao, Q.G., 2005. Study on evolution of organic carbon stock in agricultural soils of China: facing the challenge of global change and food security. Adv. Earth Sci. 20 (4), 384–393 (in Chinese).

Peng, S.B., Huang, J.L., Zhong, X.H., Yang, J.C., Wang, G.H., Zou, Y.B., Zhang, F.S., Zhu, Q.S., Buresh, R., Witt, C., 2002. Research strategy in improving fertilizer nitrogen use efficiency of irrigated rice in China. Sci. Agric. Sin. 35 (9), 1095–1103 (in Chinese).

Reay, D.S., Sabine, C.L., Smith, P., Hymus, G., 2007. Spring time for sinks. Nature 446, 727–728.

Smith, P., 2004. Carbon sequestration in croplands: the potential in Europe and the global context. Eur. J. Agronomy 20, 229–236.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H.H., Kumar, P., McCarl, B., Ogle, S., O'Mara, F., Rice, C., Scholes, R.J., Sirotenko, O., Howden, M., McAllister, T., Pan, G., Romanenkov, V., Schneider, U., Towprayoon, S., Wattenbach, M., Smith, J.U., 2008. Greenhouse gas mitigation in agriculture. Philos. Trans. R. Soc. B 363, 789–813.

Soil Survey Staff, 1994. Keys to Soil Taxonomy, sixth edition. United States Department of Agriculture, Soil Conservation Service, 161–186.

Song, J.B., 1995. A survey of straw resources and the quality from Zhejiang Province, China. Soil Fertil. 2, 23–26 (in Chinese).

Tang, G.Y., Peng, P.J., Su, Y.R., Tong, C.L., Wu, J.S., Huang, W.S., Zhu, Q.H., 2006. Content of soil organic carbon under various land-use types at farmland in Dongting Lake region. Res. Environ. Yangtze Basin 15 (2), 219–222 (in Chinese).

Vance, E.D., Brrokes, P.C., Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem. 19, 703–707.

Wang, S.J., Chen, Y., Wu, C.Y., Wang, J.Y., Li, S.Y., 2004. Long-term effect of application of different fertilizers on the crop production and soil fertility in rice fields. Acta Agric. Zhejiangensis 16 (6), 372–376 (in Chinese).

West, T.O., Marland, G., 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agric. Ecosys. Environ. 91, 217–232.

Xu, Q., 2001. Evolution of soil fertility in relation to soil quality in paddy fields of the Tai Lake area. Res. Environ. Yangtze Basin 10 (4), 323–328 (in Chinese).

Xu, X.B., Xu, X.D., Chu, Q.H., Qiu, D.S., 1999. Influence of different fertilizations in crop yield and soil fertility. In: Soil Science Society of Jiangsu (Eds.),Soil Science and Technology of Jiangsu Facing the 21th Century. Hohai University Press, Nanjing, (in Chinese), pp. 107–110.

Yao, H.Y., He, Z.L., Huang, C.Y., 1999. Effect of nitrogen fertilizer in combination with organic carbon on nitrogen availability. Agro-Environ. Protect. 18 (2), 54–56 (in Chinese).

Yao, H.Y., He, Z.L., Wilson, M.J., Campbell, C.D., 2000. Microbial biomass and community structure in a sequence of soils with increasing fertility and changing land use. Microb. Ecol. 40, 223–237.

Zhang, P.J., Li, L.Q., Pan, G.X., Zhang, J.W., 2004a. Influence of long-term fertilizer management on topsoil microbial biomass and genetic diversity of a paddy soil from the Tai Lake region, China. Acta Ecol. Sin. 24 (12), 2818–2824 (in Chinese).

Zhang, Q., Li, L.Q., Pan, G.X., Zhang, X.H., Jiang, D.A., Huang, H.G., 2004b. Dynamics of topsoil organic carbon of paddy soils at Yixing over the last 20 years and the driving factors. Quarter. Sci. 24 (2), 236–242 (in Chinese).

Zhang, Q.C., Wang, G.H., Fang, B., 2005. Influence of fertilization treatment on nutrients uptake by rice and soil ecological characteristics of soil microorganism in paddy field. Acta Pedol. Sin. 42 (1), 116–121.

Zhang, X.H., Li, L.Q., Pan, G.X., 2007. Topsoil organic carbon mineralization and CO_2 evolution of three paddy soils from South China and the temperature dependence. J. Environ. Sci. 19, 319–326 (in Chinese).

Zhang, Y., Zhu, Q.H., Qiu, D.S., Xu, X.B., Xu, X.D., 2004c. Effect of 11year continuous fertilizer application on soil carbon, nitrogen and microbial biomass of paddy soil. J. Nanjing Agric. Univ. 24 (4), 112–114 (in Chinese).

Zheng, J.F., Zhang, X.H., Li, L.Q., Zhang, P.J., Pan, G.X., 2007. Effect of long-term fertilization on C mineralization and production of CH_4 and CO_2 under anaerobic incubation from bulk samples and particle size fractions of a typical paddy soil. Agric. Ecos. Environ. 120, 129–138.

Zheng, J.F., Zhang, X.H., Pan, G.X., Li, L.Q., 2006. Diurnal variation of soil basal respiration and CO_2 emission from a typical paddy soil after rice harvest under long-term different fertilizations. Plant Nutr. Fertil. Sci. 12 (4), 485–494 (in Chinese).

Zhou, P., Zhang, X.H., Pan, G.X., 2006. Effect of long-term different fertilization on content and depth distribution of total and particulate organic carbon of a paddy soil: an example of Huangnitu from the Tai Lake region, China. Plant Nutr. Fertil. Sci. 12 (6), 765–771 (in Chinese).

Zhu, Z.L., 1997. Current status of N fertilizer application, problems and countermeasures. In: Li, Q.K., Zhu, Z.L., Yu, T.R. (Eds.), Issues of Fertilizer Application in Sustainable Agriculture of China. Jiangxi Sci. Tech. Press, Nanchang, (in Chinese), pp. 38–50.