How different long-term fertilization strategies influence crop yield and soil properties in a maize field in the North China Plain

Bingzi Zhao[1]*, Ji Chen[1], Jiabao Zhang[1], Xiuli Xin[1], and **Xiying Hao[2]**

[1] State Key Laboratory of Soil and Sustainable Agriculture, Institute of Soil Science, Chinese Academy of Sciences, PO Box 821, 71 East Beijing Road, Nanjing, 210008, China
[2] Agriculture and Agri-Food Canada, Lethbridge Research Centre, 5403 1st Ave S., Lethbridge, Alberta, T1J 4B1, Canada

Abstract

The impact of fertilization on maize (*Zea mays* L.) yield and soil properties was investigated in a long-term (> 18 y) experimental field in N China. A completely randomized block design with seven fertilizer treatments and four replications was used. The seven fertilizer treatments were (1) compost (COMP), (2) half compost plus half chemical fertilizer (COMP1/2), (3) balanced NPK fertilizer (NPK), (4–6) unbalanced chemical fertilizers without one of the major elements (NP, PK, and NK), and (7) an unamended control (CK). In addition to maize yield, soil chemical and biological properties were investigated. Compared to the balanced NPK treatment, maize yield from the COMP treatment was 7.9% higher, from the COMP1/2 was similar, but from the NP, PK, NK, and CK treatment were 12.4%, 59.9%, 78.6%, and 75.7% lower. Across the growing season, microbial biomass C and N contents, basal soil respiration, and fluorescein diacetate hydrolysis, dehydrogenase, urease, and invertase activities in the COMP and COMP1/2 treatments were 7%–203% higher than the NPK treatment. Values from all other treatments were up to 60% lower than the NPK treatment. Maize yield is closely related to the soil organic C (OC) and biological properties, and the OC is closely related to various biological properties, indicating that OC is a suitable indicator for soil quality. Our results suggest the most limiting nutrient for improving the yield or soil quality was P, followed by N and K, and balanced fertilization is important in maintaining high crop yield and soil quality. Additionally, increases in OC, N, and biological activities in COMP and COMP1/2 treatments imply that organic compost is superior to the chemical fertilizers tested.

Key words: soil organic C / enzymatic activities / microbial biomass / soil basal respiration / balanced / unbalanced fertilization

Accepted May 24, 2012

1 Introduction

Soil microbial biomass is at the center of nutrient flux in soil (*Dick*, 1992; *O'Donnell* et al., 2001). It drives the turnover of organic matter (OM) and regulates plant nutrient supply through mineralization and immobilization reactions (*Jenkinson* and *Ladd*, 1981). Soil enzymes are the biological catalysts of innumerable reactions in soils (*Dick*, 1992), and their activities provide insight into biochemical processes in soils (*Frankenberger* and *Dick*, 1983). The soil microbial-biomass content and enzymatic activities are closely related (*Zaman* et al., 1999), and increased by the C input (*Chu* et al., 2007; *Stark* et al., 2008). Thus, soil microbial biomass and enzymatic activity have been used to evaluate the impact of land-management practices on soil fertility and overall soil quality (*Franzluebbers* et al., 1995).

Fertilization has been shown to significantly affect soil microbial biomass and enzyme activities (*Marinari* et al., 2006; *Nayak* et al., 2007). The most widely used fertilization management for upland crops consists of organic compost and chemical fertilizers. Organic and inorganic fertilizers are commonly used to increase nutrient availability to plants. This is especially true for P in China, as an estimated 42.7%–47.6% of soils in China have low levels (< 10 mg P kg^{-1}) of available P or Olsen-P (*Tang* et al., 2008). Combinations of organic × inorganic fertilizers result in higher soil P contents (*Löbermann* et al., 2007) and, at the same time, organic and inorganic fertilizers can affect the function of soil microorganisms (*Marschner* et al., 2003). Long-term application of compost in a cropping system of rice–rice–fallow causes a significant increase in microbial biomass and soil enzymatic activity (*Nayak* et al., 2007). Continuous application of inorganic fertilizer can also stimulate biological activity (*Dick*, 1992; *O'Donnell* et al., 2001), because of increased soil labile-C addition from greater plant-biomass production (*Dick*, 1992).

Long-term agroecosystem experiments have been used to determine the impacts of farm-management changes on soil properties in many countries of the world (*Fließbach* et al., 2007), and a better understanding of soil biological response to management changes will provide insight into the long-term productivity of soils (*Dick*, 1992). Long-term

* Correspondence: Dr. B. Zhao; e-mail: bzhao@issas.ac.cn

experiments are essential to investigate the effects of fertilization practices on soil fertility and consequently on crop yields. The N China Plain is one of the major agricultural production areas in China, with a surface area of 350 000 km^2 containing ≈ 18 millions ha of agricultural land and a population of 203 millions (*Zhao* et al., 2007). Maize is widely grown in the Plain, with the yield making up > 32% of the total maize yield in China (*Liu* et al., 2010). To monitor crop yield and soil properties in a maize field in a long-term experiment helps for evaluating yield potential and assessing the quantity and quality of soil parameters under different equilibrium dynamics with different fertilization strategies.

Utilizing an existing long-term field experiment established in 1989 in the N China Plain (*Qin* et al., 1998), the objectives of this study are to (1) investigate the effects of long-term balanced/unbalanced fertilization on crop yield and soil properties during the maize-growing season in the 18th year and (2) evaluate the relationship between maize yield and soil properties.

2 Materials and methods

2.1 Experimental site, history of the experiment, and treatments

The long-term experimental field site is located in the Fengqiu Agroecological Experimental Station of the Chinese Academy of Sciences in Pandian, Fengqiu County, Henan Province of China (114°24′ E, 35°00′ N). The site has a typical monsoon climate with annual precipitation averaging 597 mm, of which 57% occurs from July to September, while December to February has the lowest precipitation (22 mm). The soil was classified as Calcaric Fluvisols according to WRB (*Shi* et al., 2010), which is a typical soil in the region and has a sandy-loam texture. The field has been under winter wheat (*Triticum aestivum* L.) and summer maize (*Zea mays* L.), two crops in a 1-year rotation. The winter wheat was grown from October to May and summer maize from June to September each year.

The experiment was initiated in October 1989, when the winter wheat was sown. Prior to 1989, the site was cropped without any fertilizer application for 3 y (1987–1989), to remove any residual effect from previous fertilization and obtain a uniform field site. The poor soil fertility and low soil nutrient and organic-C (OC) contents (Tab. 1) were mainly due to decades of practice by farmer that remove most crop residues from crop field and use them as fuel source for cooking and heating prior to land reform in rural China in the mid-1980s.

A completely randomized block design with seven fertilizer treatments and four replications was used. The seven fertilizer treatments were (1) compost (COMP), (2) half compost plus half chemical fertilizer (COMP1/2), (3) balanced NPK fertilizer (NPK), (4–6) unbalanced chemical fertilizers without one of the major elements (NP, PK, and NK), and (7) an unamended control (CK). Each replicate plot measured 9.5 m × 5 m and was separated by cement banks, which were 60 cm deep and extended 10 cm above the soil surface. The treatments used fertilizer-nutrient-application rates common to the region with N at 150 kg ha^{-1}, P at 32.7 kg ha^{-1}, and K at 124.5 kg ha^{-1} for winter wheat, and N at 150 kg ha^{-1}, P at 26.2 kg ha^{-1}, and K at 124.5 kg ha^{-1} for summer maize. For the COMP treatment, N was provided by application of organic compost (wheat straw mixed with soybean cake and cotton seed cake to enrich N content, composted for 2 months). The total C and N contents in the compost were determined by dichromate oxidation (*Nelson* and *Sommers*, 1982) and Kjeldahl digestion (*Bremner*, 1965), respectively. To determine the total P and K contents in the compost, samples were digested with HF-$HClO_4$ (*Jackson*, 1958), P concentration in the digesting solution was determined with the molybdenum blue method (*Lu*, 1999), and K concentration in the digesting solution was determined with a flame photometer (*Lu*, 1999). The compost contained 422 g kg^{-1}, 54.4 g kg^{-1} total N, 8.1 g kg^{-1} total P, and 19.5 g kg^{-1} total K, with a C : N ratio of 7.8. The compost-application rate for the COMP treatment was 2758 kg ha^{-1} which is equivalent to 1164 kg C ha^{-1}, 150 kg N ha^{-1}, 22.3 kg P ha^{-1}, and 53.8 kg K ha^{-1}. A half dose was applied for the COMP1/2 treatment. Thus, the total P and K amounts contained in the compost applied to the COMP and COMP1/2 treatments were less than those in the NPK treatment, and the total N contained in the compost applied to the COMP1/2 treatment was also less than that in the NPK treatment. To achieve the same levels of total N, P, and K input as those of the NPK treatment, chemical fertilizers were added to supplement the COMP and COMP1/2 treatments.

It should be noted that all of the organic compost was applied at one time and used as a basal fertilizer for each crop. The chemical-fertilizer application was consistent with standard practices of local farmers, with the P as superphosphate and K as K_2SO_4 applied as basal fertilizers. For N, 60% was applied in urea form as a basal fertilizer and 40% as topdressing for winter wheat, while 40% was applied as a basal fertilizer and 60% as topdressing for summer maize. The plants were sprayed with insecticide when worms and insects were observed. All crop-management decisions, including irrigation and weeding, were performed using the same production practices as local farmers.

Table 1: Soil pH and nutrient contents at start of the long-term experiment in 1989.

pH	OC*	TN	TP	TK	Available N	Available P	Available K
	/ g kg^{-1}				/ mg kg^{-1}		
8.65	3.43	0.45	0.50	18.6	9.51	1.93	78.8

*OC: organic C; TN: total N; TP: total P; TK: total K

2.2 Soil and plant-tissue sampling and analysis during the 2007 maize-growing season

2.2.1 Soil and plant-tissue sampling

The experiment had undergone 18 harvests of winter wheat and 17 harvests of summer maize before the 2007 maize-growing season. During this maize-growing season, fertilizers were applied on June 4 (basal dressing) and July 19 (topdressing). Maize was seeded on June 5 and harvested on September 21. Soil was sampled 5 times throughout the growing season at 1 d (June 6), 37 d (July 12), 59 d (August 3), 78 d (August 22), and 104 d (September 17 2007) after seeding, representing the growth stages of seeding, elongation, tasseling, filling, and maturity. Soil samples (0–20 cm) were collected randomly from 12 locations in each plot, and mixed as one sample.

At maturity, the maize was harvested at the soil surface with roots left in the soil. The grain and straw were separated manually from each plot, and fresh weights were obtained. The samples were then washed with tap water, rinsed with distilled water, and dried at 80°C to constant weight to obtain oven-dry weight. Oven-dried samples were ground to pass through a 0.25 mm sieve for total N-, P-, and K-content analyses. Maize grain and straw samples were digested with H_2SO_4-H_2O_2, and the N, P, and K concentrations in the digesting solution were determined using the indophenol blue method, molybdenum blue method, and a flame photometer, respectively (*Lu*, 1999; *Xu* et al., 2008). The total amounts of N, P, and K uptake by grain and straw were calculated by multiplying the concentration by the yield.

2.2.2 Analysis for soil chemical properties

Soil OC and total N (TN) contents were determined by dichromate oxidation (*Nelson* and *Sommers*, 1982) and Kjeldahl digestion (*Bremner*, 1965), respectively. Soil available N was extracted with 2 M KCl in a 1:4 solid-to-liquid ratio, shaken for 1 h, then filtered. The nitrate and ammonium concentrations in the extracting solution were determined with a Segmented Flow Analyzer (Skalar, San Plus System, The Netherlands). Soil available P was extracted by Na bicarbonate (*Olsen* et al., 1954) and K with NH_4 acetate (*Carson*, 1980), followed by P determination with the molybdenum blue method and K with a flame photometer (*Lu*, 1999; *Xu* et al., 2008). The soil available N, P, and K contents were only determined on samples collected at maturity.

2.2.3 Analysis for soil biological properties

Microbial biomass–C (C_{mic}) and microbial biomass–N (N_{mic}) contents were measured by the fumigation-extraction method as described by *Vance* et al. (1987). Briefly, 25 g fresh soil samples that have passed through a 2 mm sieve were placed in a vacuum desiccator and fumigated with ethanol-free chloroform for 24 h. Fumigated and nonfumigated samples were extracted with 50 mL 0.5 M K_2SO_4 for 30 min at 25°C and filtered. Total extractable C and N in the filtrate were determined in the same manner as soil OC and TN contents described above. For the conversion of extracted C and N to C_{mic} and N_{mic}, factors of K_{ec} = 0.38 (*Ocio* and *Brookes*, 1990) and K_{en} = 0.54 (*Brookes* et al., 1985) were used. The invertase activity (INV) was determined using sucrose as a substrate, and the urease activity (URE) was assayed using urea as a substrate (*Wang* et al., 2008; *An* et al., 2008). Dehydrogenase activity (DHD) was determined by the reduction of triphenyltetrazolium chloride (TTC) to triphenylformazan (TPF) as described by *Serra-Wittling* et al. (1995) with minor modifications as indicated by *Chu* et al. (2007). The activity of fluorescein diacetate hydrolysis (FDA) was measured following the method by *Schnürer* and *Rosswall* (1982) and *Adam* and *Duncan* (2001). All soil results reported were expressed on an oven-dried (105°C) soil-weight basis.

2.2.4 Laboratory incubation for kinetics of CO_2 evolution

Kinetics of CO_2 evolution were measured only on samples collected at seeding using the method of *Riffaldi* et al. (1996) with minor modifications. Briefly, 50 g of air-dried soil were placed in a 1 L glass jar, sufficient MilliQ water was added to bring the moisture content to 50% field capacity, and resulting mixture was incubated at 25°C for 5 d to equilibrate. The water content was adjusted back to 50% field capacity and was maintained. All soil samples were incubated in the dark. The CO_2 emitted from soil was trapped in 10 mL 0.2 M NaOH and determined after 1, 2, 3, 5, 7, 11, 16, 21, 26, 30, and 37 d of incubation. Jars without soils were also included and treated as blank. Basal soil respiration (BSR) during the incubation period was calculated by dividing the cumulative CO_2 emission by the incubation period and expressed as mg CO_2-C (kg soil)$^{-1}$ h^{-1}.

The amounts of cumulative CO_2 emitted from all soils were described as a function of incubation time (t / d). The experimental values were fitted to the following four commonly used kinetic models: (1) $C_t = C_0(1 - e^{-kt})$ (*Murwira* et al., 1990), (2) $C_t = C_0(1 - e^{-kt}) + C_1$ (*Jones*, 1984), (3) $C_t = kt^m$ (*Stanford* and *Smith*, 1972), and (4) $C_t = kt$ + intercept (*Seyfried* and *Rao*, 1988), where C_t is the cumulative C emitted as CO_2 at time t, t is the time from start of incubation, C_0 is the potentially mineralizable C, C_1 is the easily mineralizable C, and k and m are the rate constants. We selected the second model to describe our data due to the higher R^2 values from this model (ranging from 0.968 to 0.993) than values from other models (ranging from 0.940 to 0.979 for the first model, 0.902 to 0.993 for the third, and 0.912 to 0.963 for the fourth).

2.3 Statistical analysis

Soil-biological data were analyzed using the MIXED procedure (SAS Institute Inc., 2008) with fertilizer treatment, soil-sampling time, and their interactions in the model as fixed effects and replication as a random effect. Sampling time was treated as a repeated measure to account for potential correlations and different variances among sampling time. Other soil properties and crop data were also analyzed using the MIXED procedure with fertilizer treatment in the model as fixed effects and replication as a random effect. The UNIVARIATE procedure was used to check the residuals for nor-

mality and potential outliers. When an outlier was detected, it was removed before the final analysis was conducted. Various variance–covariance matrices were fitted, and the one with the lowest Akaike's Information Criterion (AIC) value was used for the final analysis. Where fertilizer-treatment differences were detected, means were separated using Tukey-Kramer test at the 0.05-probability level. When there were significant interaction effects between fertilizer treatment and sampling date, means were separated using the protected LSD test. The appropriate error term from the SAS output was used to calculate the LSD value for each treatment.

3 Results

3.1 Maize aboveground biomass and nutrient uptake

Maize grain yield in 2007, 18 y after treatment was initiated, was significantly affected by the fertilizer treatment ($P < 0.001$) in the order of COMP > COMP1/2, NPK > NP > PK > NK, CK (Tab. 2). Compared to the NPK treatment, the COMP treatment produced a significantly higher maize yield while the COMP1/2 treatment had similar yields. The unbalanced and unfertilized treatments (*i.e.,* NP, PK, NK, and CK) had significantly lower maize yields than NPK (Tab. 2). The NK treatment led to a similar maize yield as the unfertilized CK. The straw and total aboveground biomass (grain + straw) yield was also significantly affected by the fertilizer treatment ($P < 0.001$) and followed similar patterns as the grain yield. The total aboveground biomass from the COMP treatment was 8% higher than the value from the NPK treatment while the COMP1/2, NP, PK, NK, and CK treatments were 3%, 12%, 60%, 79%, and 76% lower.

The amounts of N-, P-, and K-nutrient uptake by both grain and straw followed similar patterns as the yield (Tab. 2). Greater yields were responsible for the higher nutrient uptake or *vice versa*. Additionally, the N, P, and K concentrations in grain and straw were also affected by the fertilizer treatments with values from COMP and COMP1/2 higher and from unbalanced and unfertilized treatments usually lower than the NPK treatment (data not presented).

3.2 Soil organic matter and nutrient availability

The soil OC, TN, and available N, P, and K contents were significantly affected by the fertilizer treatment ($P < 0.001$) with average OC values in the order of COMP > COMP1/2 > NPK > NP > PK > NK, CK, and average TN values in the order of COMP > COMP1/2 > NPK, NP > PK, NK > CK (Tab. 3). The

Table 2: Maize aboveground biomass and nutrient uptake from different fertilization treatments after 18 y of establishment.

	Biomass			N uptake			P uptake			K uptake		
Treatment*	grain	straw	total	grain	straw	total	grain	straw	total	grain	straw	total
	/ kg ha^{-1}											
COMP	9 820 a#	8 416 a	18 237 a	125 a	75 a	200 a	26 a	7 a	33 a	38 a	218 a	256 a
COMP1/2	9 082 b	7 372 b	16 453 b	112 b	59 b	171 b	21 b	5 b	26 b	35 b	178 b	213 b
NPK	9 262b	7 637 b	16 899 b	111 b	66 b	177 b	20 b	5 b	26 b	35 b	188 b	222 b
NP	8 280 c	6 528 c	14 809 c	99 c	59 b	158 c	19 b	5 b	24 b	29 c	55 d	84 c
PK	3 150 d	3 621 d	6 771 d	25 d	17 c	42 d	8 c	6 b	14 c	12 d	79 c	91 c
NK	1 493 e	2 116 e	3 609 e	18 e	19 c	37 d	2 d	1 c	3 d	5 e	44 de	49 d
CK	1 528 e	2 579 e	4 107 e	16 e	18 c	34 d	2 d	1 c	3 d	5 e	33 e	38 d

* Treatments are explained in section 2.1. Data in a column followed by different lowercase letters indicate significant differences at 0.05-probability levels based on protected Tukey-Kramer test.

Table 3: Effect of fertilizer treatment on soil organic C, total N, and available N, P, and K contents.

Treatment*	Organic C	Total N	Available N	Available P	Available K
	/ g kg^{-1}		/ mg kg^{-1}		
COMP	9.19 a#	1.24 a	14.9 b	12.4 b	141.6 c
COMP1/2	7.03 b	0.99 b	12.2 bc	9.6 c	120.2 d
NPK	5.25 c	0.72 c	9.0 cd	6.7 d	125.6 d
NP	4.77 d	0.69 c	12.2 bc	7.2 d	47.2 e
PK	3.96 e	0.56 d	6.9 c	20.2 a	275.8 b
NK	3.54 f	0.54 d	21.2 a	1.1 e	306.9 a
CK	3.33 f	0.49 e	6.7 c	1.1 e	61.3 e

* Treatments are explained in section 2.1. Data in a column followed by different lowercase letters differ at 0.05-probability levels based on protected Tukey-Kramer test.

highest soil available N content was from the NK treatment, lowest from the PK and unfertilized CK, with values from other treatments in between (Tab. 3). The highest available P content was from the PK treatment, the lowest from the NK and CK treatments, while the highest available K content come from the NK treatment and the lowest from the NP and CK treatments (Tab. 3).

3.3 Kinetics of cumulative CO_2 emission and mineralizable C in soil

Microbial activity, as measured by the cumulative CO_2 emission from soil over the 37 d, showed that for all treatments, a larger initial CO_2 emission was followed by a slower rate throughout the remaining incubation period (Fig. 1). The average BSR across the entire incubation period in soil was significantly affected by fertilizer treatment *(P* < 0.001) with average BSR values in the order of COMP > COMP1/2 > NPK > NP > PK > NK, CK (Tab. 4). The BSR rate from the COMP and COMP1/2 treatments was 36% and 25% higher than the balanced NPK treatment while those in the unbalanced fertilizer and CK treatments were 10% to 39% lower. The C_0 and C_1 values followed similar trends as soil OC content and BSR with values from the COMP treatment the highest and from NK and CK treatments the lowest, and both were significantly affected by fertilizer treatment (P < 0.001) (Tab. 4).

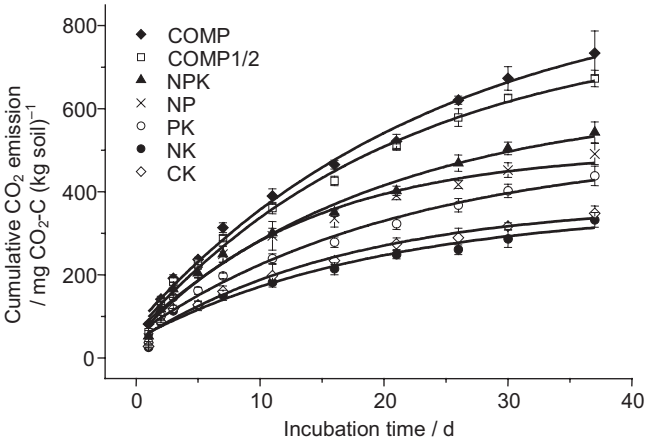

Figure 1: Cumulative CO_2-C emissions as affected by fertilization treatments. (Vertical bars are standard errors of means; n = 4.) Treatments are explained in section 2.1.

Table 4: Effect of fertilizer treatment on the basal soil respiration rate (BSR), potential and easily mineralizable C in soil.

Treatment*	BSR	Mineralizable C	
		potential (C_0)	easily (C_1)
	/ mg CO_2-C kg^{-1} h^{-1}	/ mg kg^{-1}	
COMP	0.86 a#	900 a	78 a
COMP1/2	0.76 b	740 b	65 ab
NPK	0.61 c	560 c	64 b
NP	0.55 d	470 d	63 b
PK	0.49 e	455 d	57 bc
NK	0.37 f	324 e	45 cd
CK	0.39 f	336 e	40 d

* Treatments are explained in section 2.1. Data in a column followed by different lowercase letters differ at 0.05-probability levels based on protected Tukey-Kramer test.

3.4 Soil microbial biomass and enzyme activity

3.4.1 Microbial biomass

The contents of C_{mic} and N_{mic} were significantly affected by the fertilizer treatment (P < 0.001), sampling date (P < 0.001), and their interactions (P < 0.001 for C and P = 0.017 for N). Generally, the size of C_{mic} from the COMP and COMP1/2 treatments was 8%–126% and of N_{mic} was 7%–138% higher than the from NPK treatment, while the sizes in the unbalanced fertilization treatments and CK were 15%–55% lower for C_{mic} and 27%–79% lower for N_{mic}, regardless of the growth stage (Tab. 5). The C_{mic} and N_{mic} contents were significantly higher in the COMP treatment than other treatments in most cases except for the COMP1/2 treatment. Additionally, the NK and CK treatments usually had the lowest C_{mic} and N_{mic} contents at each growth stage, with C_{mic} and N_{mic} in the NP and PK treatments being between the NPK and NK and/or CK treatments (Tab. 5). The contents of C_{mic} and N_{mic} varied over the growing season, with the C level increasing initially, reaching a peak at the tasseling stage and then decreasing afterward, reaching the lowest levels at maturity. The N_{mic} contents peaked at the elongation stage, with values in other growth stages less variable (Tab. 5).

3.4.2 Enzymatic activity

Similar to the C_{mic} and N_{mic}, the enzymatic activities examined in our study were also affected by fertilizer treatment (P < 0.001), sampling date (P < 0.001), and their interactions (P < 0.001). The activity of invertase (INV), urease (URE), dehydrogenase (DHD), and fluorescein diacetate hydrolysis (FDA) in the treatments with organic compost (*i.e.*, COMP and COMP1/2 treatments) was 14%–45%, 24%–114%, 22%–99%, and 14%–203% higher than their respective values from the NPK treatment throughout the growth season. In the unbalanced fertilization treatments and CK, the levels of these enzyme activities were lower than in the NPK treatment in most instances (Tab. 5). The enzymatic activities in the NP treatment were usually higher than the PK treatment, while the NK and CK treatments had the lowest levels with little difference between them (Tab. 5).

There were no consistent patterns in enzymatic activities over the growing season although there were variations. In most instances, INV activity did not differ significantly among the growth stages, while URE activity showed some variations with highest values occurring at maturity (Tab. 5). For the DHD activity, however, the values generally decreased with plant growth to a minimum at the filling stage regardless of the fertilization treatments, and increased

Table 5: Soil microbial biomass C and N and enzymatic activities as affected by fertility treatment and sampling dates over the growing season.

	Treatment*	Seeding	Elongation	Tasseling	Filling	Maturity
C_{mic}	COMP	615 a§ B#	427 a CD	928 a A	450 a C	363 a D
/ mg C kg^{-1}	COMP1/2	416 b B	397 ab BC	627 b A	330 b C	282 a C
	NPK	369 bc B	249 bc C	519 c A	224 c C	172 b C
	NP	293 cde B	262 abc BCD	471 c A	205 c C	141 bc D
	PK	322 cd A	187 c BC	276 d AB	161 d C	140 bc C
	NK	262 de A	228 bc AB	165 e B	146 de B	96 bc B
	CK	237 e A	274 abc AB	287 d A	134 e B	70 c B
N_{mic}	COMP	73.2 a BC	106.2 a A	62.3 a C	70.2 a B	81.3 a B
/ mg N kg^{-1}	COMP1/2	35.7 ab C	99.6 ab A	38.0 bc C	60.0 b B	66.3 b B
	NPK	19.1 bc D	73.1 bc A	48.1 ab BC	57.4 b AB	42.0 c C
	NP	18.0 cd C	54.1 cd A	25.5 cd B	29.6 cd B	35.0 cd B
	PK	13.5 bc B	50.6 cde A	30.8 cd AB	31.5 c AB	26.3 d B
	NK	10.1 bcd B	23.5 e A	36.8 bcd A	26.8 cd AB	24.3 d AB
	CK	4.3 d B	33.7 de A	21.2 d A	21.1 d A	32.1 cd A
INV	COMP	961 a C	1125 a A	1212 a A	1088 a AB	1027 a B
/ mg glucose kg^{-1} h^{-1}	COMP1/2	903 a B	908 b B	991 b AB	958 b AB	979 b A
	NPK	752 b BC	782 c B	915 b A	838 b AB	708 c C
	NP	767 b A	623 d B	775 c A	829 b A	603 d B
	PK	616 c A	393 e C	693 c A	648c A	468 e B
	NK	489 d A	360 e B	550 d A	466 d A	352 f B
	CK	490 d A	393 e B	546 d A	419 d AB	348 f B
URE	COMP	70.9 a B	93.7 a A	75.3 a B	70.9 a B	96.3 a A
/ mg NH_4-N kg^{-1} h^{-1}	COMP1/2	54.6 b D	70.0 b B	61.0 b C	63.0 b C	92.9 a A
	NPK	43.1 c B	44.8 d B	46.7 c B	44.4 c B	66.3 b A
	NP	43.3 c C	59.3 c A	48.4 c B	43.2 c C	59.3 c A
	PK	30.1 d C	32.6 e C	37.5 d B	30.9 d C	44.5 d A
	NK	23.7 e C	26.7 f BC	28.8 e B	27.6 de BC	37.7 e A
	CK	25.1 e B	31.5 e A	31.9 e A	25.8 e B	28.5 f AB
DHD	COMP	10.5 a A	9.0 a B	8.1 a C	7.3 a D	8.3 a C
/ mg TPF kg^{-1} h^{-1}	COMP1/2	8.5 b A	7.5 b B	7.2 b B	5.3 b D	6.1 b C
	NPK	5.3 d AB	5.9 c A	5.9 c A	4.0 c C	4.7 c B
	NP	6.1 c A	5.5 c A	4.8 c B	3.5 d C	4.7 c B
	PK	5.1 d A	4.1 d B	4.8 d AB	2.7 e C	4.4 c B
	NK	3.7 e A	2.6 e B	3.0 e B	2.0 f C	2.4 d BC
	CK	3.4 e A	3.0 e AB	3.2 de A	1.8 f C	2.4 d B
FDA	COMP	33.5 a AB	35.1 a AB	34.9 ab AB	30.4 a B	42.1 a A
/ mg fluorescein kg^{-1} h^{-1}	COMP1/2	19.7 b C	13.9 b D	41.4 a A	25.0 b B	18.0 b CD
	NPK	11.1 c C	7.0 d D	30.7 bc A	20.6 c B	20.6 b B
	NP	17.7 b B	13.1 b C	23.0 d A	14.9 d C	19.6 b AB
	PK	11.3 c C	12.8 b C	25.5 cd A	12.5 e C	18.3 b B
	NK	8.4 d B	12.7 b A	14.1 e A	7.3 f B	8.0 c B
	CK	10.5 c BC	9.7 c BC	12.5 e AB	12.4 e A	8.3 c C

* Treatments are explained in section 2.1. C_{mic}: microbial biomass C, N_{mic}: microbial biomass N; INV: invertase activity; URE: urease activity: DHD: dehydrogenase activity; FDA: fluorescein diacetate hydrolysis activity.

§ Numbers in a column followed by different lowercase letters indicate treatment effect and numbers in a row followed by different uppercase letters indicate sampling-date effect at 0.05-probability levels based on protected Fisher LSD test.

thereafter (Tab. 5). The FDA activity at different stages generally followed a similar pattern as C_{mic} in the soil samples (Tab. 5).

3.5 Relationship between aboveground maize biomass and soil properties

Correlation analyses revealed strong positive relationships among total maize aboveground biomass, the OC, TN, C_{mic}, and N_{mic} contents, enzymatic activities, and BSR (Tab. 6). In

Table 6: Pearson's correlation coefficients for aboveground maize biomass and soil properties.

	Biomass[a]	Organic C	Total N	Microbial C	Microbial N	INV	URE	DHD	FDA
Organic C	0.820*								
Total N	0.823*	0.998**							
C_{mic}	0.833*	0.989**	0.987**						
N_{mic}	0.818*	0.979**	0.965**	0.973**					
INV	0.935**	0.964**	0.965**	0.955**	0.945**				
URE	0.896**	0.982**	0.985**	0.977**	0.948**	0.991**			
DHD	0.880**	0.982**	0.981**	0.978**	0.965**	0.988**	0.992**		
FDA	0.816*	0.984**	0.979**	0.990**	0.978**	0.953**	0.969**	0.986**	
BSR	0.904**	0.966**	0.963**	0.949**	0.953**	0.993**	0.986**	0.990**	0.957**

§ Treatments are explained in section 2.1. C_{mic}: microbial biomass C, N_{mic}: microbial biomass N; INV: invertase activity; URE: urease activity: DHD: dehydrogenase activity; FDA: fluorescein diacetate hydrolysis activity; BSR: basal soil respiration rate

[a] The maize biomass results were obtained at harvest. Results of soil properties are means of five sampling dates except BSR results which were obtained only at sowing. $n = 20$ ($n = 4$ for BSR).

* significant at $P < 0.05$; ** significant at $P < 0.01$.

addition, statistically significant correlations amongst all the soil properties were also found (Tab. 6). That is to say, maize yield was closely correlated with soil OM and soil biological properties.

4 Discussion

4.1 Long-term fertilization and soil-nutrient availability

Fertilizer applications and organic-N mineralization would increase the available N pools in soil while crop uptake, leaching, and gaseous losses will decrease them (*Meng* et al., 2005; *Zhao* et al., 2007). The higher soil available N content with compost than the balanced NPK-fertilizer application observed in our study is consistent with results reported by *Marinari* et al. (2006) when comparing continuous application of poultry manure *vs.* chemical fertilizers over 7 y. The high plant-available N content associated with compost reflects the slow-release nature of organic N to available forms, less leaching or gaseous N loss right after application since a similar amount of N was applied in both the COMP and NPK treatments, and a higher crop N uptake in the COMP than NPK treatment. The higher soil OC content with compost applications will also help improve soil structure, and increase nutrient-holding capacity (*Rasool* et al., 2008). Both would contribute to the higher available N content in soil. While the NPK, NP, and NK treatments received the same amount of N each year, the elevated soil available N content in the NK (relative to the NPK and NP) treatment (Tab. 3) was mainly due to less crop uptake (Tab. 2) and more N left in the soil after maize harvest.

The available P content is the amount of P potentially available for crop growth and is primarily soluble and adsorbed P in soil. The observed higher available P content in COMP than the NPK treatment reflected (1) the slow release of available P from the applied compost; (2) greater mineralization and available-P release through increased microbial activities (Fig. 1); and (3) increases in P solubility by OM application (*Sanyal* and *De Datta*, 1991) as soluble C competes with P for sorption sites (*Ohno* and *Crannell*, 1996; *Erich* et al., 2002). Similar to N, the higher available P content in the PK than the NP and treatments was mainly due to reduced uptake (Tab. 2). The very low contents of available P observed in the NK and CK treatments were chiefly attributable to 18 y of continuous K uptake by crops any supplement.

The higher available K content in compost than balanced-NPK-fertilizer-applied soil can be attributed to the increased CEC as OM increased in soil associated with compost applications (*Bronick* and *Lal*, 2005). Similar to N and P, the higher available K content in the NK than the PK and NPK treatments was mainly due to differences in crop K uptake (Tab. 2).

4.2 Long-term fertilization and soil organic C

Soil OC content is one of the most important indicators of soil fertility. The significantly higher OC content in the COMP and COMP1/2 treatments suggests that continuous long-term application of organic compost improves soil fertility. Among the chemical-fertilization treatments, the decreasing order of NPK > NP > PK > NK, CK for soil OC implies that P was the most important element in improving soil fertility in the N China Plain, and N and K were the second and third important elements.

The higher soil OC content in the COMP and COMP1/2 treatments directly resulted from application of organic compost and indirectly through increased crop root and root exudates since all the aboveground biomass was removed from the field. Our results are consistent with a general pattern of soil OC content increasing linearly with the amount of organic input (*Carter*, 2002) and crop yield (*Lal*, 2002; *Smith*, 2004). Greater amounts of organic compost applied in the COMP than COMP1/2 treatment as well as higher yields in the COMP than COMP1/2 treatment (Tab. 2) is responding to the higher OC content in the COMP than COMP1/2 treatment (Tab. 3).

For the NPK, NP, PK, NK, and CK treatments, crop roots and root exudates were the only sources of organic-C input into the soils. Thus, variations in OC among these balanced/unbalanced chemical-fertilization treatments should be mainly due to differences in the amount of the crop roots and root exudates, which correspond to yield variations presented in Tab. 2.

4.3 Soil organic C and soil biological properties

All of the biological properties correlated significantly with OC (Tab. 6). These positive relationships are consistent with results from other studies (*e.g., Dick*, 1992; *Nayak* et al., 2007; *Stark* et al., 2007, 2008). In general, management practices that increase the inputs of organic residues, either from plants or animal manure, will increase microbial biomass content and enzymatic activities (*Dick*, 1992; *Buchanan* and *King*, 1992; *Böhme* et al., 2005; *Stark* et al., 2008) because higher levels of soil OC result in an increased availability of C substrate that stimulates microbial activity and, therefore, enzyme activities (*Nayak* et al., 2007). Thus, in our study, we infer that the differences in the microbial biomass and enzymatic activity among fertilization treatments were mainly attributable to the corresponding changes in soil OC, which was modified by the long-term-fertilization management practices.

Our study also suggests that the COMP and COMP1/2 treatments consistently led to the highest level of various biological properties among the fertilization treatments, and this trend persisted during the maize-growing season (Fig. 1, Tab. 5). This result may be partially explained by the estimated C_0 values (Tab. 4). Higher levels of C_0 from the COMP and COMP1/2 treatments indicated a larger and more active microbial biomass, which may have persisted longer in the soils from the COMP and COMP1/2 treatments as a result of increased availability of readily mineralizable nutrients and C (energy source).

4.4 Soil biological properties and maize growth stage

Another observation from the present study is that the measured soil biological properties showed temporal variations but the variation patterns were not consistent (Tab. 5). These kinds of inconsistent temporal patterns for various biological properties have also been reported by other researchers on maize (*Chu* et al., 2005), wheat (*Jin* et al., 2009; *Mandal* et al., 2007), rice (*Nayak* et al., 2007), and soybean (*Aon* and *Colaneri*, 2001) during the growing season, or during a period under fallow (*Marinari* et al., 2006). A possible explanation is that enzymatic activities have strong relationships with soil physico-chemical properties, but each has different sensitivity to the same physico-chemical variable (*Aon* and *Colaneri*, 2001), such as soil moisture, soil temperature, and the ratio of soil OC and total N, all of which change over the growing season (*Aon* and *Colaneri*, 2001; *Chu* et al., 2005; *Jin* et al., 2009).

The general temporal pattern of C_{mic} obtained from the present study (Tab. 5) was completely opposite to the pattern reported by *Chu* et al. (2005), who showed that C_{mic} gradually decreased to a minimum at the active growth stage followed by a quick increase in the later period of the maize-growing season. They attributed their observed pattern to the change in soil moisture content when expressed as water-filled pore space. In our study, we did not find any significant correlations between C_{mic} and soil moisture (data not presented). We speculate that rhizosphere conditions induced by plant growth stages might play a major role in enhancing C_{mic}. The peak C_{mic} content at tasseling stage reflects the vegetative growth which is greatest around this time and that stimulates more root supply of soil labile C (*Buchanan* and *King*, 1992). An increase in C_{mic} related to increased plant production has been reported in a tallgrass prairie ecosystem (*Garcia* and *Rice*, 1994). *Srivastava* and *Singh* (1991) found a positive relationship between total plant biomass or root biomass and C_{mic}. It has also been suggested that the rhizodeposits could stimulate biological activities (*Kuzyakov*, 2002). This explains the FDA activity in our study.

The rapid reduction in N_{mic} from elongation to tasseling (Tab. 5) may be attributed to (1) the large amount of N needed to support the rapid maize growth during this time, and (2) N loss by leaching due to frequent rainfall (*i.e.*, from mid-July to early August, data not presented). In a tallgrass prairie ecosystem, *Garcia* and *Rice* (1994) reported that decreases of N_{mic} coincided with plant N uptake.

The relatively high levels of URE activity at maturity could probably be attributed to the minimum inorganic-N level at that time, mainly due to plant uptake and N loss by various ways. A negative relationship between URE activity and the application rate of inorganic N has been reported (*Dick*, 1992), because URE is involved in N-releasing processes, with NH_4^+-N being the end product of URE (*Dick*, 1992). During the rice-growing season, *Pattnaik* et al. (1999) found that the highest URE activity occurred at maturity stage under field conditions.

The DHD only exists in viable cells (*Dick*, 1992). Our previous report showed that the increases in DHD activity and C_{mic} were proportional to exposure to drying–rewetting cycles (*Zhao* et al., 2010). However, in the present study, an inconsistent temporal pattern of C_{mic} and DHD activity during the maize-growing season was observed (Tab. 5). Similar inconsistent temporal patterns have been reported by *Chu* et al. (2005) and *Mandal* et al. (2007). During the maize-growing season, *Chu* et al. (2005) attributed the lowest C_{mic} and highest DHD activity observed in early August to high root activity at that time, while during the wheat-growing season, *Mandal* et al. (2007) did not provide any explanation for the highest values of C_{mic} observed at stages of tillering and flowering but not for the DHD activity. The mechanisms for the temporal variation in DHD activity warrant further investigation.

4.5 Maize yield and its relationship with soil properties

Since crop yield is mainly controlled by the availability of major essential macronutrients (N, P, K) in the N China Plain,

the balanced fertilization with organic compost and/or chemical fertilizers resulted in greater maize biomass than unbalanced chemical fertilization, as indicated by decreasing order of COMP > COMP1/2, NPK > NP > PK > NK, CK (Tab. 2). The results also indicated that continuous application of organic compost was beneficial for yield improvement when compared to the NPK treatment; supplying half the N required by compost produced the same yield as supplying all the required N as fertilizer. The yield order of NPK > NP > PK > NK, CK implied that the most limiting nutrient for maize yield was P, followed by N and K.

Soil available P was almost depleted following 18 y of continuous P uptake by crops without any P supplement in the NK treatment (Tab. 3). Addition of N and K fertilizer caused further P imbalance, and resulted in an even lower yield in the NK than the CK treatment (Tab. 2). Unlike nutrient P, nutrient N has been reported to be supplemented from deposition with up to 45.6 kg N ha^{-1} in a agro-ecosystem in the N China Plain (*Huang* et al., 2011). Nutrient K was the least limiting nutrient for maize yield, probably because the soil in the studied area was rich in K. However, with continuous K consumption in the NP treatment, the significantly reduced available K content as presented in Tab. 3 suggests the necessity of K application in the studied area after 18 y continuous unbalanced fertilization with N and P but without K.

Significantly positive relationships between maize yield and OC, TN, soil microbial biomass, and enzyme activities were consistent with those reported by *Tejada* et al. (2008) and *Jagadamma* et al. (2008). Our previous report showed that soils with higher OC content had a higher functional stability in response to drying and rewetting stress (*Zhao* et al., 2010), indicating greater buffer capacity when suffering from unfavorable soil or climate conditions. In addition, increased OC content decreases bulk density increases total porosity as well as water-holding capacity, and improves aggregation even in deeper soil layers (*Rasool* et al., 2008), all of which might benefit plant growth. In addition, the bioavailability of various nutrients for plants increased by soil microbial biomass and enzyme activities (*Tejada* et al., 2008), which consequently resulted in positive relationships between maize yield and various biological properties (Tab. 6).

5 Conclusions

Eighteen years after establishment of the field trial, continuous annual application of organic compost increased maize yield and improved various soil properties, even when half of the N required was supplied by compost. Unbalanced inorganic fertilization (NP, PK, and NK treatments) usually led to significant lower maize yields, relative to balanced N, P, and K fertilization. For the unbalanced fertilization and CK treatments, soil nutrients and enzymatic activities were generally lower when compared to the NPK treatment. The most limiting nutrient was P, followed by N and K. Our results highlighted the importance of balanced fertilization, especially with organic compost, in maintaining and enhancing crop yield and soil quality. The significantly positive relationship between soil OC and various biological properties suggests that OC can be an appropriate indicator for soil quality in the N China Plain.

Acknowledgments

This project was supported by *the National Basic Research Program of China (973 Program) (2011CB100506),* by the *National Natural Science Foundation of China (41271311)*, and by the *Knowledge Innovation Program of the Chinese Academy of Sciences (ISSASIP1118, KSCX2-EW-N-08).* We would like to thank Dr. *Haiyan Chu* of the Institute of Soil Science, Chinese Academy of Sciences, for his helpful suggestions in preparing the manuscript.

References

Adam, G., Duncan, H. (2001): Development of a sensitive and rapid method for the measurement of total microbial activity using fluorescein diacetate (FDA) in a range of soils. *Soil Biol. Biochem.* 33, 943–951.

An, S., Zheng, F., Zhang, F., Pelt, S. V., Hamer, U., Makeschin, F. (2008): Soil quality degradation processes along a deforestation chronosequence in the Ziwuling area, China. *Catena* 75, 248–256.

Aon, M. A., Colaneri, A. C. (2001): Temporal and spatial evolution of enzymatic activities and physico-chemical properties in an agricultural soil. *Appl. Soil Ecol.* 18, 255–270.

Böhme, L., Langer, U., Böhme, F. (2005): Microbial biomass, enzyme activities and microbial community structure in two European long-term field experiments. *Agric. Ecosyst. Environ.* 109, 141–152.

Bremner, J. M. (1965): Total nitrogen, in Black, C. A., Evans, D. D., Ensminger, L. E., White, J. L., Clark, F. E., Dinauer, R. C. (eds): Methods of Soil Analysis, Part 2, Chemical and Microbiological Properties. Agronomy No. 9. American Society of Agronomy, Madison, WI, USA, pp. 1149–1178.

Bronick, C. J., Lal, R. (2005): Soil structure and management: a review. *Geoderma* 124, 3–22.

Brookes, P. C., Landman, A., Pruden, G., Jenkinson, D. S. (1985): Chloroform fumigation and the release of soil nitrogen: a rapid extraction method to measure microbial biomass nitrogen in soil. *Soil Biol. Biochem.* 17, 837–842.

Buchanan, M., King, L. D. (1992): Seasonal fluctuations in soil microbial biomass carbon, phosphorus, and activity in no-till and reduced-chemical-input maize agroecosystems. *Biol. Fertil. Soils* 13, 211–217.

Carson, P. L. (1980): Recommended potassium test, in Dahnke, W. C. (ed.): Recommended Chemical Soil Test Procedures for the North Central Region. Bulletin 499, North Dakota Agricultural Experiment Station, Fargo, ND, USA, pp. 17–18.

Carter, M. R. (2002): Soil quality for sustainable land management: Organic matter and aggregation interactions that maintain soil functions. *Agron. J.* 94, 38–47.

Chu, H. Y., Hosen, Y., Yagi, K., Okada, K., Ito, O. (2005): Soil microbial biomass and activities in a Japanese Andisol as affected by controlled release and application depth of urea. *Biol. Fertil. Soils* 42, 89–96.

Chu, H., Lin, X., Fujii, T., Morimoto, S., Yagi, K., Hu, J., Zhang, J. (2007): Soil microbial biomass, dehydrogenase activity, bacterial community structure in response to long-term fertilizer management. *Soil Biol. Biochem.* 39, 2971–2976.

Dick, R. P. (1992): A review: long-term effects of agricultural systems on soil biochemical and microbial parameters. *Agric. Ecosyst. Environ.* 40, 25–36.

Erich, M. S., Fitzgerald, C. B., Porter, G. A. (2002): The effect of organic amendments on phosphorus chemistry in a potato cropping system. *Agric. Ecosyst. Environ.* 88, 79–88.

Fließbach, A., Oberholzer, H., Gunst, L., Mäder, P. (2007): Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. *Agric. Ecosyst. Environ.* 118, 273–284.

Frankenberger, W. T. Jr., Dick, W. A. (1983): Relationships between enzyme activities and microbial growth and activity indices in soil. *Soil Sci. Soc. Am. J.* 47, 945–951.

Franzluebbers, A. J., Zuberer, D. A., Hons, F. M. (1995): Comparison of microbiological methods for evaluating quality and fertility of soil. *Biol. Fertil. Soils* 19, 135–140.

Garcia, F. O., Rice, C. W. (1994): Microbial biomass dynamics in tallgrass prairie. *Soil Sci. Soc. Am. J.* 58, 816–823.

Huang, P., Zhang, J., Zhu, A., Xin, X., Zhang, Ch., Ma, D. (2011): Atmospheric deposition as an important nitrogen load to a typical agroecosystem in the Huang-Huai-Hai Plain. 1. Measurement and preliminary results. *Atmos. Environ.* 45, 3400–3405.

Jackson, M. L. (1958): Soil Chemical Analysis. Prentice-Hall, Inc., Englewood Cliffs, NJ, pp. 111–133.

Jagadamma, S., Lal, R., Hoeft, R. G., Nafziger, E. D., Adee, E. A. (2008): Nitrogen fertilization and cropping system impacts on soil properties and their relationship to crop yield in the central Corn Belt, USA. *Soil Tillage Res.* 98, 120–129.

Jenkinson, D. S., Ladd, J. N. (1981): Microbial biomass in soil: measurement and turnover. *Soil Biochem.* 5, 415–471.

Jin, K., Sleutel, S., Buchan, D., De Neve, S., Cai, D.X., Gabriels, D., Jin, J. Y. (2009): Changes of soil enzyme activities under different tillage practices in the Chinese Loess Plateau. *Soil Tillage Res.*104, 115–120.

Jones, C. A. (1984): Estimation of an active fraction of soil nitrogen. Commun. *Soil Sci. Plant Anal.* 15, 23–32.

Kuzyakov, Y. (2002): Review: factors arhizosphere priming effect. *J. Plant Nutr. Soil Sci.*165, 382–396.

Lal, R. (2002): Soil carbon dynamics in cropland and rangeland. *Environ. Pollut.* 116, 353–362.

Löbermann, B. E., Köhne, S., Köppen, D. (2007): Effect of organic, inorganic, and combined organic and inorganic P fertilization on plant P uptake and soil P pools. *J. Plant Nutr. Soil Sci.* 170, 623–628.

Liu, Q., Zhang, J., Xu, M., Zhang, B. (2010): The effect of climate changes on maize yield in a long-term fertilization experiment in the Huang-Huai-Hai Plain of China. *J. Food Agric. Environ.* 8, 754–758.

Lu, R. (1999): Methods of Analysis on Soil Agricultural and Chemical Properties. (in Chinese) China Agricultural and Scientific Technology Press, pp. 146–316.

Mandal, A., Patra, A. K., Singh, D., Swarup, A., Masto, R. E. (2007): of long-term application of manure and fertilizer on biological and biochemical activities in soil during crop development stages. *Bioresour. Technol.* 98, 3585–3592.

Marinari, S., Mancinelli, R., Campiglia, E., Grego, S. (2006): Chemical and biological indicators of soil quality in organic and conventional farming systems in Central Italy. *Ecol. Indic.* 6, 701–711.

Marschner, P., Kandeler, E., Marschner, B. (2003): Structure and function of the soil microbial community in a long-term fertilizer experiment. *Soil Biol. Biochem.* 35, 453–461.

Meng, L., Ding, W., Cai, Z. (2005): Long-term application of organic manure and nitrogen fertilizer on N_2O emissions, soil quality and crop production in a sandy loam soil. *Soil Biol. Biochem.* 37, 2037–2045.

Murwira, H. K., Kirchmann, H., Swift, M. J. (1990): The effect of moisture on the decomposition rate of cattle manure. *Plant Soil* 122, 197–199.

Nayak, D. R., Babu, Y. J., Adhya, T. K. (2007): Long-term application of compost influences microbial biomass and enzyme activities in a tropical Aeric Endoaquept planted to rice under flooded condition. *Soil Biol. Biochem.* 39, 1897–1906.

Nelson, D. W., Sommers, L. E. (1982): Total Carbon, Organic Carbon and Organic Matter, in Page, A. L., Miller, R. H., Keeney, D. R. (eds): Methods of Soil Analysis, Part 2. American Society of Agronomy, Madison, WI, USA, pp. 539–579.

Ocio, J. A., Brookes, P. C. (1990): An evaluation of methods for measuring the microbial biomass in soils following recent additions of wheat straw, and the characterization of the biomass that develops. *Soil Biol. Biochem.* 22, 685–694.

O'Donnell, A. G., Seasman, M., Macrae, A., Waite, I., Davies, J. T. (2001): Plant and fertilizers as drivers of change in microbial community structure and function in soils. *Plant Soil* 232, 135–145.

Ohno, T., Crannell, B. S. (1996): Green and animal manure-derived organic matter effects on phosphorus sorption. *J. Environ. Qual.* 25, 1137–1143.

Olsen, S. R., Cole, C. V., Watanabe, F. S., Dean, L. A. (1954): Estimation of Available Phosphorus in Soils by Extraction with Sodium Bicarbonate. USDA Circ. No. 939, USDA, Washington, DC, USA, pp. 19.

Pattnaik, P., Mallick, K., Ramakrishnan, B., Adhya, T. K., Sethunathan, N. (1999): Urease activity and urea hydrolysis in tropical flooded soil unplanted or planted to rice. *J. Sci. Food Agric.* 79, 227–231.

Qin, S. W., Gu, Y. C., Zhu, Z. L. (1998): A preliminary report on long-term stationary experiment on fertility evolution of fluvo-aquic soil and the effect of fertilization (in Chinese). *Acta Pedologica Sinica* 35, 367–375.

Rasool, R., Kukal, S. S., Hira, G. S. (2008): Soil organic carbon and physical properties as affected by long-term application of FYM and inorganic fertilizers in maize–wheat system. *Soil Tillage Res.* 101, 31–36.

Riffaldi, R., Saviozzi, A., Levi-Minzi, R. (1996): Carbon mineralization kinetics as influenced by soil properties. *Biol. Fertil. Soils* 22, 293–298.

Sanyal, S. K., De Datta, S. K. (1991): Chemistry of phosphorus transformations in soil. *Adv. Soil Sci.* 16, 1–120.

Schnürer, J., Rosswall, T. (1982): Fluorescein diacetate hydrolysis as a measure of total microbial activity in soil and litter. *Appl. Environ. Microbiol.* 43, 1256–1261.

Serra-Wittling, C., Houot, S., Barriuso, E. (1995): Soil enzymatic response to addition of municipal solid-waste compost. *Biol. Fertil. Soils* 20, 226–236.

Seyfried, M. S., Rao, P. S. C. (1988): Kinetics of nitrogen mineralization in Costa Rican soils: Model evaluation and pretreatment effects. *Plant Soil* 106, 159–169.

Shi, X. Z., Wang, H. J., Warner, E. D., Yu, D. S., Sun, W. X., Zhao, Y. C. (2010): Cross-reference for relating Genetic Soil Classification of China with WRB at different scales. *Geoderma* 154, 344–350.

Smith, P. (2004): Carbon sequestration on croplands: the potential in Europe and the global context. *Eur. J. Agron.* 20, 229–236.

Srivastava, S. C., Singh, J. S. (1991): Microbial-C, microbial-N, and microbial-P in dry tropical forest soils–Effects of alternate land-uses and nutrient flux. *Soil Biol. Biochem.* 23, 117–124.

Stanford, G., Smith, S. J. (1972): Nitrogen mineralization potentials of soils. *Soil Sci. Soc. Am. P.* 36, 465–472.

Stark, C., Condron, L. M., Stewart, A., Di, H. J., O'Callaghan, M. (2007): Effects of past and current crop management on soil microbial biomass and activity. *Biol. Fertil. Soils* 43, 531–540.

Stark, C. H., Condron, L. M., O'Callaghan, M., Stewart, A., Di, H. J. (2008): Differences in soil enzyme activities, microbial community structure and short-term nitrogen mineralization resulting from farm management history and organic matter amendments. *Soil Biol. Biochem.* 40, 1352–1363.

Tang, X., Li, J., Ma, Y., Hao, X., Li, X. (2008): Phosphorus efficiency in long-term (15 years) wheat-maize cropping systems with various soil and climate conditions. *Field Crops Res.* 108, 231–237.

Tejada, M., Gonzalez, J. L., García-Martínez, A. M., Parrado, J. (2008): Effects of different green manures on soil biological properties and maize yield. *Bioresour. Technol.* 99, 1758–1767.

Vance, E. D., Brookes, P. C., Jenkinson, D. S. (1987): An extraction method for measuring microbial biomass C. *Soil Biol. Biochem.* 19, 703–707.

Wang, Q. K., Wang, S. L., Liu, Y. X. (2008): Response to N and P fertilization in a young *Eucalyptus dunnii* plantation: Microbial properties, enzyme activities and dissolved organic matter. *Appl. Soil Ecol.* 40, 484–490.

Xu, M., Li, D., Li, J., Qin, D., Yagi, K., Hosen, Y. (2008): Effects of organic manure application with chemical fertilizers on nutrient absorption and yield of rice in Hunan of Southern China. *Agric. Sci. China* 7, 1245–1252.

Zaman, M., Di, H. J., Cameron, K. C., Frampton, C. M. (1999): Gross nitrogen mineralization and nitrification rates and their relationships to enzyme activities and the soil microbial biomass in soils treated with dairy shed effluent and ammonium fertilizer at different water potentials. *Biol. Fertil. Soils* 29, 178–186.

Zhao, B. Z., Zhang, J. B., Flury, M., Zhu, A. N., Jiang, Q. A., Bi, J. W. (2007): Groundwater contamination with NO_3-N in a wheat-corn cropping system in the North China Plain. *Pedosphere* 17, 721–731.

Zhao, B., Chen, J., Zhang, J., Qin, S. (2010): Soil microbial biomass and activity response to repeated drying-rewetting cycles along a soil fertility gradient modified by long-term fertilization management practices. *Geoderma* 160, 218–224.