Nutr Cycl Agroecosyst (2007) 79:17–34
DOI 10.1007/s10705-006-9070-6

RESEARCH ARTICLE

Crop residue, manure and fertilizer in dryland maize under reduced tillage in northern China: II nutrient balances and soil fertility

Xiaobin Wang · Willem B. Hoogmoed · Dianxiong Cai · Udo D. Perdok · Oene Oenema

Received: 29 June 2006 / Accepted: 14 November 2006 / Published online: 14 July 2007
© Springer Science+Business Media B.V. 2007

Abstract A long-term experiment was carried out in the dryland of northern China to assess the effects of applications of maize stover, cattle manure and NP (1:0.44) fertilizer on partial nitrogen (N), phosphorus (P) and potassium (K) balances, extractable soil N (SEN), P and K, and soil organic matter (SOM) in a spring maize cropping system, under reduced tillage conditions. The experiment was set-up according to an incomplete, optimal design, with three factors at five levels and 12 treatments, including a control with two replications. Statistical analyses using multiple regression models showed that the partial N, P and K balances were strongly influenced by annual variations in the amounts of soil water at seeding (SWS) and growing season rainfall (GSR). Most treatments had positive P but negative N and K balances. Cumulative P and K balances were reflected in extractable soil P (P-Olsen) and K (exchangeable K), but the weak relationships indicated that the sorption of P and buffering of K were strong. Cumulative balances of effective organic carbon (C) were weakly related to soil organic C (SOC) content after 12 years. Negative C balances were related to decreases in SOC, but positive C balances were not translated into increases in SOC. The analysis of nutrient balances and soil fertility indices revealed that nutrient inputs in most treatments were far from balanced. It is concluded that the concepts of 'ideal soil fertility level' and 'response nutrient management' provide practical guidelines for improving nutrient management under the variable rainfall conditions of dry land areas in northern China.

Keywords Crop residue · Dryland · Fertilizer · Maize · Manure · Nitrogen · Nutrient balances · Nutrient management · Soil fertility · Soil organic carbon

Introduction

China has a long tradition of efficient recycling of organic residues in agriculture, but this tradition is rapidly disappearing following the intensification of agricultural production, the increased use of mineral fertilizers and the increasing urbanization and decoupling of crop production and animal production (Ju et al. 2005; Yang 1996). The intensification of

X. Wang (✉) · D. Cai
Institute of Agricultural Resources and Regional Planning, and Ministry of Agriculture Key Laboratory of Plant Nutrition and Nutrient Cycling, Chinese Academy of Agricultural Sciences, 12 Zhongguancun Nandajie, 100081 Beijing, China
e-mail: xiaobin.wang@wur.nl

X. Wang · W. B. Hoogmoed · U. D. Perdok
Farm Technology Group, Wageningen University, P.O. Box 43, 6700 AA Wageningen, The Netherlands

O. Oenema
Environmental Sciences, Wageningen University, P.O. Box 8005, Wageningen, The Netherlands

agricultural production has greatly increased the volume of agricultural production, but, at the same time, it has contributed to a decrease in resource use efficiency, land degradation through increased wind and water erosion, and to pollution of groundwater and surface waters (Zhang et al. 2005; Rozella et al. 1997; Liu and Diamond 2005; Liu et al. 2005). China is at a crossroads of its agricultural, industrial and environmental developments. It faces the challenges of drastically increasing resource utilization through combining insights and practices from history with the current reality. Both short-term remedies and longer-term adjustments are needed for sustaining food and feed production while safeguarding the natural environment (Rosegrant and Cai 2001; Zhang et al. 2005).

The dryland farming regions of northern China provide food to a large fraction of the increasing Chinese population. This area is vulnerable to wind and water erosion and to environmental degradation, due to its inherent soil and climatic characteristics (Wang et al. 2006, 2007b) and its current management practices. Continuous maize (*Zea mays* L.) or wheat (*Triticum aestivum* L.), and wheat–maize rotations, are the dominant cropping systems. The current practice is to remove crop residues from the field after harvest to feed animals or to use it as biofuel, with little or no return of manure and ashes to the fields where the crop residues came from. Burning crop residues in the field is also a common practice in some areas. After harvest, the soil is ploughed and ploughed once again in spring before seeding. These practices contribute to a decrease in soil organic carbon (SOC) content (Yang 1996) and to soil drying and severe wind erosion in winter and early spring (Wang et al. 2006). Further, recommendations for fertilizer applications are based on potential yields and do not make provision for differences in soil fertility and for other possible nutrient sources. In practice, the uniform 'blanket' fertilizer recommendations are often exceeded with, as a consequence, low nutrient use efficiencies. Evidently, there is an increasing need to refocus current practices and recommendations so that multiple goals can be matched; i.e., sustained high crops yields and efficient resource utilization.

In the current study, alternative nutrient management practices under reduced tillage were evaluated, to minimize soil drying and wind erosion in spring and, at the same time, to improve soil fertility and nutrient use efficiencies. Alternative practices included the incorporation in the soil of various mixtures of maize stover, manure and mineral fertilizer in fall and to seed in spring without prior soil cultivation. The effectiveness of these practices was assessed in a long-term field experiment in Shanxi province in northern China. The reduced tillage practice has been shown to be highly effective in decreasing wind erosion (Cai et al. 2002; Wang et al. 2006). Effects of applying organic residues and mineral fertilizer in autumn on grain yields and nitrogen (N), phosphorus (P) and potassium (K) use efficiencies have been reported in Wang et al. (2007a). This paper discusses partial N, P and K balances and the changes in soil organic matter (SOM) and soil fertility indices for P and K.

Nutrient input–output balances of agroecosystems provide insight into the cycling and use efficiency of nutrients and in possible nutrient losses from these systems to the wider environment (Goodlass et al. 2003; Oborn et al. 2003; Zebarth et al. 1999). Positive balances are expected to result ultimately in environmental pollution, and negative balances in soil depletion and ultimately to loss of productivity. However, the impact of a balance cannot be seen independently from actual soil fertility. At low fertility levels, nutrient balances should be positive, to build up soil fertility to the target level, while, at high fertility levels, balances should be negative, to avoid environmental pollution (Janssen and de Willigen 2006a, b). Hence, nutrient balances should be evaluated concomitant with the assessment of soil fertility, and vice versa.

Materials and methods

Site description

The ongoing long-term field experiment was started in 1992 at the Dryland Farming Experimental Station in Shouyang, Shanxi province (112°–113° E, 37°–38° N) in northern China. The area has a mean altitude of 1,100 m above sea level and a continental monsoon climate with an average annual rainfall of 520 mm. Severe erosion in the past has led to the formation of a hilly landscape. The dominant cropping system is continuous spring maize, which accounts for over 50% of the total area for crop production. The study area is representative of a typical farming region dependent on rainfall. Spring drought is often a limiting factor for seed germination and the emergence and growth of spring maize. The experimental site has a sandy loam cinnamon soil, classified as calcaric–fluvic cambisols (Institute of Soil Science, Chinese Academy of Science, ISS-CAS 2003; IUSS 2006). At the start, in 1992, soil pH was 7.9, and SOC and soil organic N (SON) content was 15 g kg^{-1} and 1.0 g kg^{-1}, respectively. Available soil P and soil K in the top 20 cm of soil were low to medium, judged on the basis of P-Olsen (7.3 mg kg^{-1}) and NH_4OAc extractable K (2.2 mmol kg^{-1}).

Experimental design

The experiment was set-up according to an incomplete, optimal design (Xu 1988) with three factors (NP fertilizer, maize stover and cattle manure) at five levels and 12 treatments, including a control treatment and two replications. Fertilizer NP (ratio $N:P_2O_5$ = 1:1) applications were 0, 31, 105, 179 and 210 kg ha^{-1}. Maize stover applications were 0, 879, 3,000, 5,121 and 6,000 kg ha^{-1}. Cattle manure applications were 0, 1,500, 3,000, 4,500 and 6,000 kg ha^{-1} (also Wang et al. 2007a).

Methods

Field experiment and measurement

Plots of 6 × 6 m^2 were laid down randomly in duplicate. Locally recommended maize varieties were used, i.e., Yandan no. 12 in 1993–1997, Shandannong no. 1 in 1998, and Jindan no. 34 in 1999–2004. The N and P fertilizers were urea (46% N) and superphosphate (16% P_2O_5) in a ratio of N to P_2O_5 of 1:1. Maize stover and cattle manure were obtained from local farms. The weighed mean content of organic matter, total N, total P (as P_2O_5) and total K, was 75%, 0.63%, 0.09% and 0.72% for maize stover (ratio of N:P:K = 100:6:114) and 36%, 0.96%, 0.39% and 0.74% for cattle manure (ratio of N:P:K = 100:18:77), respectively. Maize stover, cattle manure and fertilizers were broadcast and incorporated into the soil after maize harvest in the fall by ploughing (20 cm deep). Seeding was done in spring, usually at the end of April, without any tillage. Maize was seeded in rows at distances of 30 cm within the rows and 60 cm between rows (plant density 55,555 ha^{-1}). Weeding was done manually twice during the growing season. Maize was harvested close to the ground with sickles, and all harvested biomass was removed from the plots, usually in October.

Grain yield and crop residues (rachis + stems + leaves + husks) were determined by harvesting the center 1.8 × 2.1 m^2 of the plots. Samples of grain and corn residues were oven dried at 70°C to a uniform weight and then weighed. Harvest index (HI) was estimated as the ratio of grain to total aboveground biomass yield. Plant samples of grain and stover were analyzed for total N by the Kjeldahl method, total P by the H_2SO_4–$HClO_4$ method and total K by the HNO_3–$HClO_4$ flame photometry methods (Westerman 1990). Plant analyses of N and P were started in 1993, that of K in 1997. Grain yields and N, P and K uptakes have been described in detail in Wang et al. (2007a).

Soil samples were taken at seeding to determine soil water at seeding (SWS), and after harvest to determine extractable N, P and K. Each sample was a composite of three random 2-cm diameter cores per plot, taken at depths of 0–20, 20–40, 40–60, 60–80, and 80–100 cm. Samples were analyzed for extractable soil N (SEN), by the alkali-hydrolytic diffusion method (Keeney and Nelson 1982). Extractable soil P (SEP) was determined by Olsen's method, and extractable soil K (SEK) with 1 M NH_4OAc. SOC was determined in the 0–20 cm and 20–40 cm layers by wet oxidation (using H_2SO_4–$K_2Cr_2O_7$).

Nutrient and carbon balance estimation

Partial N, P or K balances were estimated per treatment from measured N, P or K inputs and outputs, using the following equations (in kilograms per hectare):

$$\mathrm{NPK_{inputs}} = \mathrm{NP_{fertilizer}} + \mathrm{NPK_{stover}} + \mathrm{NPK_{manure}} \qquad (1)$$

$$\mathrm{NPK_{outputs}} = \mathrm{NPK_{uptake\ in\ aboveground\ biomass}}$$

$$\mathrm{NPK_{balance}} = \mathrm{NPK_{inputs}} - \mathrm{NPK} \qquad (2)$$

$\mathrm{NP_{fertilizer}}$ is the added N and P via fertilizer, $\mathrm{NPK_{stover}}$ the added N, P and K via stover,

$\mathrm{NPK}_{\mathrm{manure}}$ the added N, P and K via manure, and $\mathrm{NPK}_{\mathrm{uptake\backslash;in\backslash;aboveground\backslash;biomass}}$ the N, P and K taken up in the above-ground biomass of maize. The soil C balance was estimated per treatment and year as follows:

$$
\begin{aligned}
\mathrm{C}_{\mathrm{input}} &= \mathrm{C}_{\mathrm{stover}} + \mathrm{C} + \mathrm{C}_{\mathrm{stubble+roots}} \\
\mathrm{C}_{\mathrm{output}} &= \mathrm{k}_{\mathrm{stover}} {}^{*} \mathrm{C} + \mathrm{k}_{\mathrm{manure}} {}^{*} \mathrm{C}_{\mathrm{manure}} \\
&\quad + \mathrm{k}_{\mathrm{stubble+roots}} {}^{*} \mathrm{C}_{\mathrm{stubble+roots}} + \mathrm{k}_{\mathrm{SOM}} {}^{*} \mathrm{C}_{\mathrm{SOM}} \\
\mathrm{C}_{\mathrm{balance}} &= \mathrm{C}_{\mathrm{input}} - \mathrm{C}_{\mathrm{output}}
\end{aligned}
$$

Where $\mathrm{C}_{\mathrm{stover}}$ = the input of C via added stover, in kilograms per hectare; $\mathrm{C}_{\mathrm{manure}}$ = the input of C via added manure, in kilograms per hectare; $\mathrm{C}_{\mathrm{stubble+roots}}$ = the input of C via stubble and roots left on the field after harvest, estimated at 20% of the above-ground biomass at harvest (Zhang et al. 1984), in kilograms per hectare; $\mathrm{C}_{\mathrm{SOM}}$ = the amount of soil C (0–20 cm) after harvest, using a bulk density of 1.2 mg m^{-3}; $\mathrm{k}_{\mathrm{stover}}$ = decay constant of added stover in the first year, dimensionless; $\mathrm{k}_{\mathrm{manure}}$ = decay constant of added manure in the first year, dimensionless; $\mathrm{k}_{\mathrm{stubble+roots}}$ = decay constant of stubble and roots during the first year, dimensionless; $\mathrm{k}_{\mathrm{SOM}}$ = decay constant of SOM, dimensionless. Decay constants were taken from the literature (Table 1). Because of the uncertainty in the actual decay constants, simple sensitivity analyses were done by varying the k values in the balance equations.

Statistical analysis

Multivariate regression analysis was used to examine relationships between N, P and K balances and added NP fertilizer, stover and manure, growing season rainfall (GSR) and SWS. Extractable soil N, P and K (SEP and SEK) were also related to added NP fertilizer, stover and manure, GSR and SWS, using general linear models (GLMs), and regression (REG) procedures of the SAS Institute 2004. The data were subjected to an analysis of variance using the GLM procedure, and the mean pairwise comparison was based on the DUNCAN test at the 0.05 probability level (at $P \leq 0.05$).

Table 1 Decay coefficients for stover, manure, stubble + roots and soil organic matter (SOM) in the calculation of C balances. Three sets of literature values have been used

Stover	Manure	Stubble + roots	SOM	Literature
0.6	0.8	0.6	0.02	Janssen (1992)
0.67	0.56	0.55	0.02	Yang (1996)
0.8	0.48	0.55	0.0285	Cai (1996)

Results

Partial N, P, K and C balances

Mean N balances ranged from −84 kg ha^{-1} year^{-1} for the control treatment to 90–99 kg ha^{-1} year^{-1} for treatments with high NP fertilizer application rates (Table 2). Approximately half of the treatments had a negative partial N balance. At modest application rates of NP fertilizer (*F*), stover (*S*) and manure (*M*) in treatment 11 ($F = 105$, $S = 3{,}000$, $M = 3{,}000$), N inputs equaled N outputs. However, these partial balances do not account for N inputs via atmospheric deposition (approximately 10 kg ha^{-1} year^{-1}; Duan et al. 2001) and net mineralization of SOM, and they do not account for possible N losses via erosion, ammonia volatilization, denitrification and leaching. Yet, mean N surpluses were significantly related to SEN after harvest ($R^2 = 0.63$).

Mean P balances ranged from −12 kg ha^{-1} year^{-1} for the control treatment to 74 kg ha^{-1} year^{-1} for treatment 7 with the highest NP fertilizer application rate (Table 2). Most treatments had a highly positive P balance. Only the two treatments (treatments 8 and 12) that did not receive NP fertilizer had a negative P balance. The results indicate that applications exceeding 31 kg $\mathrm{P_2O_5}$ fertilizer (equivalent to 13.5 kg P) led to a mean P surplus. Surpluses of P were linearly related to mean extractable soil P (SEP, or P-Olsen) ($R^2 = 0.85$).

Mean K balances ranged from −43 kg ha^{-1} year^{-1} to 12 kg ha^{-1} year^{-1} (Table 2). Most treatments had a negative K balance, including the treatment with the highest mean grain yield (treatment 9). Only treatments with relatively large inputs of stover and manure, combined with sub-optimal or above-optimal N fertilizer inputs (treatments 5 and 6), had a slightly positive K balance. The negative K balances suggest that the soil K pool was depleted, but K balances were poorly related to mean exchangeable soil K ($R^2 = 0.21$).

Table 2 Effects of NP fertilizer (*F*), maize stover (*S*) and manure (*M*) in various combinations on mean grain yield (*GY*), mean partial N, P, K and C balances, and mean extractable soil N (*SEN*), P (*SEP*) and K (*SEK*) at harvest time in the top 20 cm layers per treatment for the whole experimental period (1993–2004). For the calculation of C balances, use was made of decay coefficients from (a)Janssen (1992), (b) Yang (1996) and (c) Cai (1996). Note, treatments are arranged in the order of increasing grain yields (see text). Values with the same letter within a column are not significantly different at the 5% level

Treatment	Added *F*, *S* and *M*, respectively, (kg ha^{-1})			GY * (kg ha^{-1})		N balance (kg ha^{-1})		P balance (kg ha^{-1})		K balance (kg ha^{-1})		C balance (a) (kg ha^{-1})		C balance (b) (kg ha^{-1})		C balance (c) (kg ha^{-1})		SEN (mg kg^{-1})		SEP (mg kg^{-1})		SEK (mg kg^{-1})		SOM (g kg^{-1})[0]	
12	0	0	0	4587	E	−84	H	−12	G	−40	F	−370	I	−330	H	−622	H	64	D	7	F	93	C	24.7	D
8	0	3000	1500	5139	D	−69	G	−11	G	−18	BCD	215	F	244	F	−211	F	71	CD	16	E	104	BC	26.3	AB
3	31	879	4500	5805	C	−40	F	4	F	−13	B	53	G	303	E	36	D	75	ABC	17	DE	98	BC	24.8	BCD
10	105	0	1500	6269	BC	−26	E	29	DE	−43	F	−222	H	−94	G	−366	G	73	BC	26	BC	98	BC	25.1	ABCD
4	179	879	4500	6420	B	79	B	65	B	−21	BCD	65	G	320	E	45	D	82	A	32	AB	99	BC	25.5	ABCD
5	31	5121	4500	6433	B	−21	E	4	F	12	A	775	B	899	AB	375	B	81	A	18	DE	105	BC	26.2	ABC
7	210	3000	1500	6512	B	90	AB	74	A	−24	CD	310	E	349	E	−99	E	80	AB	36	A	101	BC	25.6	ABCD
2	105	3000	0	6528	B	−24	E	27	E	−35	EF	272	E	236	F	−227	F	72	CD	23	CD	98	BC	24.8	CD
6	179	5121	4500	6668	AB	99	A	65	B	6	A	794	B	922	A	394	AB	82	A	36	A	107	BC	26.5	A
11	105	3000	3000	6740	AB	0	D	31	D	−26	DE	402	D	520	D	99	D	76	ABC	32	AB	104	BC	25.5	ABCD
1	105	3000	6000	7114	A	20	C	34	C	−15	BC	545	C	817	C	444	A	83	A	31	AB	121	A	25.7	ABCD
9	105	6000	1500	7184	A	−3	D	28	E	−25	CD	900	A	856	BC	240	C	79	ABC	22	CDE	108	B	25.4	ABCD

* From: Wang et al. (2007a)

Calculated mean C balances ranged from −622 kg ha^{-1} year^{-1} to 922 kg ha^{-1} year^{-1} (Table 2). Balances were negative for treatments with relative low inputs of stover and manure. Balances were highly sensitive to the choice of the decay coefficients, especially to k_{stover} and k_{SOM}. The significant differences between treatments in C balances led to slight but significant differences in mean SOM levels; the treatment with the lowest mean C balance had the lowest mean SOM content. The squared (Pearson) correlation coefficient (R^2) for the relationship between the mean C balance and the overall mean SOM was 0.4. The use of a decay coefficient for SOM of 0.0285, as derived for Shouyang by Cai (1996), gave lower cumulative C balances than did the use of the mean value for northern China (0.02) estimated by Yang (1996). Cumulative C balances over the 12-year experimental period ranged from −7,500 kg ha^{-1} to 4,700 kg ha^{-1} when Cai's coefficients were used, and from −4,000kg ha^{-1} to 11,000 kg ha^{-1} when Yang's coefficients were used. This indicates that maximal differences between treatments in input of effective C were in the range of 12,200 kg ha^{-1} to 15,000 kg ha^{-1} over the whole experimental period.

Balances of NPK and C per treatment and year

Annual variations in partial N, P and K balances per treatment are shown in Fig. 1. Variations between years increased in the order: P balances <K balances <N balances. Annual variations within treatments were up to 100 kg ha^{-1} for N balances, 50 kg ha^{-1} for K balances and up to 20 kg ha^{-1} for P balances. With time, negative N balances tended to become less negative and positive balances more positive, because grain yields and N uptake tended to decrease over time (Wang et al. 2007a). This decreasing trend was most clear in treatments providing little or no NP fertilizer (treatments 8, 12 and 3).

Variations in N, P and K balances were related to added fertilizer, stover (except for P balances) and manure, and to SWS and GSR, except for K balances (Table 3). The negative regression coefficients for SWS and GSR reflect increased NPK uptakes and, hence, less positive balances during wet years than during dry years. Potassium balances were not related to SWS and GSR, possibly because K balances were established only from 1997

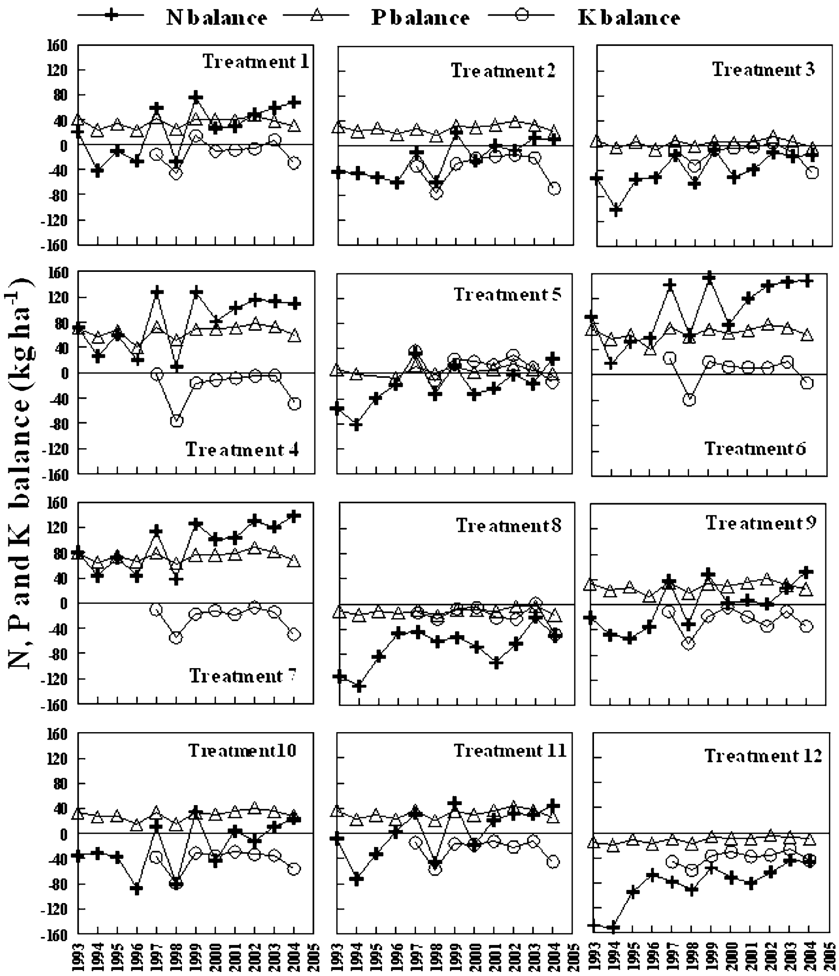


Fig. 1 Partial N, P and K balance per treatment during the experimental period 1993–2004. *Lines between plots* are shown only for reasons of clarity. Note that K balances only started in 1997

onwards and because variations in SWS and GSR were relatively small during the period 1997–2004 (Wang et al. 2007a).

Annual variations in balances of effective C were relatively small, with maximal differences between years within treatments of 500 kg ha^{-1} year^{-1}, nearly independent of the choice of decay coefficient for SOM (Fig. 2). Variations in C balance were related to added fertilizer, stover and manure, and to SWS but not to GSR (Table 3). The positive regression coefficients for SWS reflect increased stover and stubble production in wet spring (years). In contrast to the N balances, the C balances tended to become less positive (or more negative), because yield of above-ground biomass tended to decrease over time, as a result of decreasing yields (Wang et al. 2007a).

Extractable soil N and total SOC per treatment and year

Extractable soil N at harvest was relatively high, with values ranging from 30 mg kg^{-1} to 120 mg kg^{-1} in the top 20 cm (Fig. 3). With depth, SEN tended to decrease, except for the treatments providing N fertilizer at rates ≥ 105 kg ha^{-1} year^{-1}. Also in the control treatment (treatment 12), SEN was relatively high, with values ranging from 30 mg kg^{-1} to 90 mg kg^{-1} in the topsoil and from 20 mg kg^{-1} to 60 mg kg^{-1} in the subsoil, while maize suffered from N shortage in most years (Wang et al. 2007a). These relatively high values suggest that not all extractable N, determined by the alkali-hydrolytic diffusion method, was plant-available N. The relatively high SEN values are probably related to the decomposition

Table 3 Coefficients of the regression models for partial N, P and K balances (in kilograms per hectare), and extractable soil N (*SEN*), P (*SEP*) and K (*SEK*) (in milligrams per kilogram). The dependent variables added were : NP fertilizer, stover and manure, GSR and soil water at sowing (SWS). For fertilizer (*Fsq*) and GSR (*GSRsq*) quadratic relationships were also examined. *PE* parameter estimate, *SE* standard error, *Pr* probability value (*P* value)

Dependent variable		Intercept (b0)	Fertilizer (b1)	Stover (b2)	Manure (b3)	GSR (b4)	SWS (b5)	Fsq (b11)	GSRsq (b44)
N balance	PE	13.5	0.21	0.004	0.01	-0.13	−0.15	0.003	0.000
$R^2 = 0.74$, $n = 128$	SE	35.1	0.15	0.002	0.00	0.09	0.07	0.001	0.000
	t-value	0.39	1.40	2.22	4.97	−1.43	−2.21	3.57	0.43
	Pr > $\lvert t\rvert$	0.70	0.16	0.03	<0.0001	0.16	0.03	0.001	0.67
P balance	PE	26.1	0.34	0.000	0.001	−0.07	−0.06	0.000	0.000
$R^2 = 0.94$, $n = 127$	SE	7.07	0.03	0.000	0.000	0.02	0.01	0.000	0.000
	t-value	3.70	11.1	−0.19	3.95	−3.82	−4.53	2.00	3.15
	Pr > $\lvert t\rvert$	0.0003	<0.0001	0.85	0.0001	0.0002	<0.0001	0.05	0.002
K balance	PE	−21.8	−0.28	0.005	0.006	−0.07	0.01	0.001	0.000
$R^2 = 0.42$, $n = 92$	SE	34.7	0.10	0.001	0.001	0.12	0.06	0.000	0.000
	t-value	−0.63	−2.86	4.59	5.84	−0.60	0.25	2.53	0.20
	Pr > $\lvert t\rvert$	0.53	0.005	<0.0001	<0.0001	0.55	0.80	0.01	0.84
C balance_Janssen	PE	−894	1.84	0.18	0.04	0.57	0.92	−0.01	0.000
$R^2 = 0.87$, $n = 128$	SE	154	0.67	0.01	0.01	0.39	0.29	0.003	0.000
	t-value	−5.81	2.73	24.96	6.03	1.49	3.18	−2.3	−0.67
	Pr > $\lvert t\rvert$	<0.001	0.007	<0.001	<0.001	0.14	0.002	0.023	0.50
C balance_Yang	PE	−936	2.05	0.15	0.09	0.72	1.04	−0.01	0.000
$R^2 = 0.85$, $n = 128$	SE	168	0.73	0.01	0.01	0.42	0.32	0.003	0.000
	t-value	−5.58	2.79	19.17	11.98	1.71	3.3	−2.34	−0.88
	Pr > $\lvert t\rvert$	<0.001	0.006	<0.001	<0.001	0.09	0.001	0.021	0.38
C balance_Cai	PE	−1175	2.14	0.09	0.11	0.47	1.02	−0.01	0.000
$R^2 = 0.76$, $n = 128$	SE	187	0.82	0.01	0.01	0.47	0.35	0.004	0.000
	t-value	−6.3	2.62	10.49	12.56	1	2.91	−2.23	−0.22
	Pr > $\lvert t\rvert$	<0.001	0.01	<0.001	<0.001	0.32	0.004	0.028	0.82
SEN_0−20 cm	PE	166	0.05	0.001	0.002	−0.26	−0.11	−0.000	0.000
$R^2 = 0.37$, $n = 128$	SE	14.3	0.06	0.001	0.001	0.04	0.03	0.000	0.000
	t-value	11.6	0.76	1.50	2.56	−7.17	−4.05	−0.11	6.32
	Pr > $\lvert t\rvert$	<0.0001	0.45	0.14	0.01	<0.001	<0.001	0.91	<0.001
SEN_20−40 cm	PE	146	0.09	0.000	0.001	−0.22	−0.12	0.000	0.000
$R^2 = 0.50$, $n = 127$	SE	12.5	0.05	0.001	0.001	0.03	0.02	0.000	0.000
	t-value	11.74	1.66	0.22	1.60	−6.95	−5.19	0.33	5.65
	Pr > $\lvert t\rvert$	<0.001	0.10	0.82	0.11	<0.001	<0.001	0.74	<0.001
SEP_0−20 cm	PE	38.7	0.17	0.000	0.001	0.01	−0.08	−0.000	−0.000
$R^2 = 0.47$, $n = 128$	SE	10.4	0.05	0.001	0.001	0.03	0.02	0.000	0.000
	t-value	3.73	3.84	0.48	1.91	0.39	−4	−1.27	−1.09
	Pr > $\lvert t\rvert$	0.001	0.001	0.63	0.059	0.70	0.001	0.21	0.28
SEK_0−20 cm	PE	101	0.06	0.002	0.002	−0.008	−0.02	−0.000	0.000
$R^2 = 0.09$, $n = 93$	SE	24.2	0.07	0.001	0.001	0.09	0.04	0.000	0.000
	t-value	4.16	0.91	2.27	2.38	−0.10	−0.48	−1.01	0.05
	Pr > $\lvert t\rvert$	<0.001	0.37	0.03	0.02	0.92	0.64	0.32	0.96

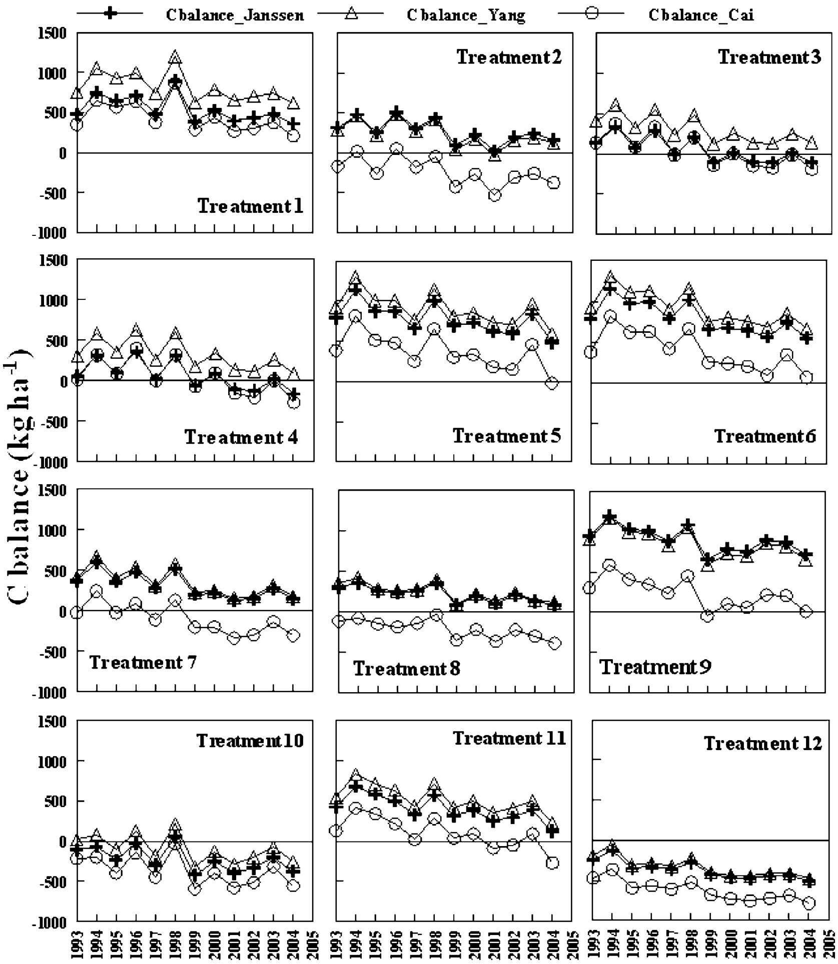


Fig. 2 Calculated C balances per treatment during the experimental period 1993–2004. Balances were calculated from different decay coefficients, following Janssen (1992), Yang (1996) and Cai (1996). See also the text. *Lines between plots* are shown only for reasons of clarity

of labile organic N compounds, such as glucosamine, during the extraction, as discussed by Keeney and Nelson (1982). The alkali-hydrolytic diffusion method is still widely used in China, because of its low costs and simplicity, but the major soil laboratories have discarded this method because of its potential of overestimating soil mineral N (Dr. Ju Xiaotang, 2006, personal communication). Here, SEN values will be discussed only to compare treatments in a relative sense.

In the topsoil, SEN was slightly higher in the manure and fertilizer treatments than in the control treatment, but differences were relatively small and varied greatly from year to year (Fig. 3). In contrast, subsoil layers exhibited increasing differences between the control treatment and treatments providing N fertilizer at rates ≥ 105 kg ha^{-1} year^{-1}. The accumulation of SEN in subsoil layers suggests downward movement of N through leaching. Accumulation of SEN in the subsoil was most pronounced in treatment 7, which provided the highest N fertilizer doses, and in the second half of the experimental period, when above-ground biomass and N uptake were relatively low.

Annual variations in SEN were strongly related to SWS and GSR; the higher the SWS and GSR, the lower the SEN in the 0–20 cm and 20–40 cm layers (Table 3). These inverse relationships are caused by the positive relationship between SWS and N uptake, and GSR and N uptake. However, the significant linear and quadratic relationship between GSR and SEN may also point to N losses via leaching and possibly denitrification in wet years. Interestingly, SEN in the 0–20 cm layers was related to added manure but not to added N fertilizer (Table 3).

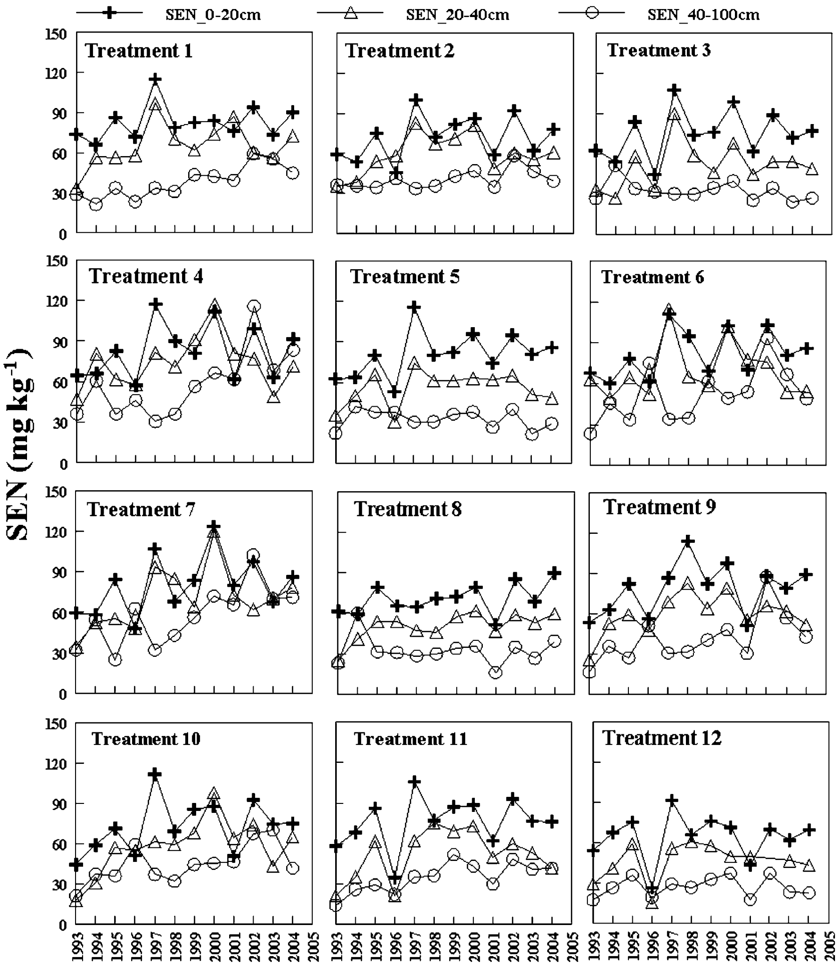


Fig. 3 Extractable soil N (SEN) at the end of the growing season per treatment for soil depth 0–20 cm, 20–40 cm and 40–60 cm. *Lines between plots* are shown only for reasons of clarity

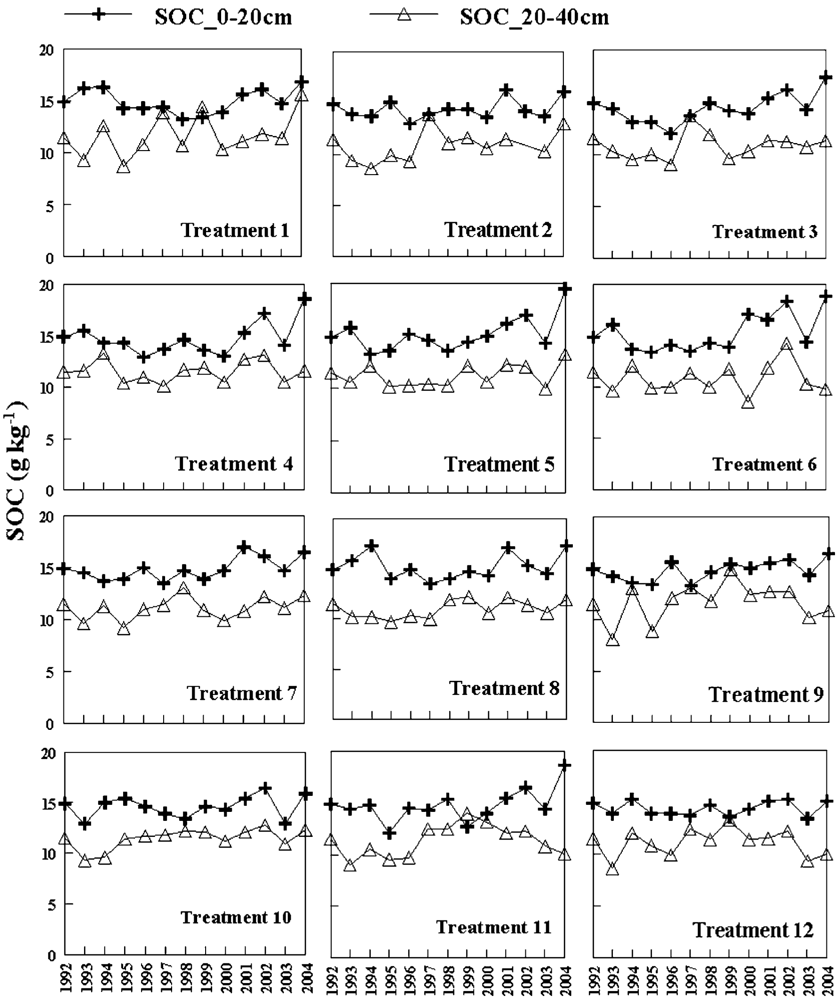
Soil organic carbon in the top 20 cm and in the 20–40 cm layer did not change much over time, and differences between treatments at the end of the experimental period were relatively small (Fig. 4). In treatments providing relatively large amounts of stover, manure and N fertilizer, topsoil SOC tended to increase with time. At the end of the experimental period, average SOC in the topsoil was 15.7 ± 0.9 g kg^{-1}, which was 0.8 g kg^{-1} higher than at the start of the experiment. In the 20–40 cm layer, mean SOC content was 11.2 g kg^{-1}. Differences between topsoil and subsoil did not increase over time.

Extractable soil P and K per treatment and year

Extractable P (SEP) in the topsoil was strongly related to added NP fertilizer and also to added manure (Table 3). In all treatments SEP tended to increase with time, except for the control treatment (Fig. 5), which had a strong negative P balance. Treatment 8 also exhibited an increase in SEP in the topsoil from 7 cm to about 20 mg kg^{-1}, even though the P balance was highly negative (Table 2, Fig. 1). This suggests a priming effect; the added stover and manure in treatment 8 have contributed to increasing the extractability of soil P (P-Olsen). This effect was most noticeable during the first half of the experimental period. In the control treatment, SEP ranged between 5 mg kg^{-1} and 9 mg kg^{-1} (mean 7 mg kg^{-1}) and tended to decrease over time.

With time, SEP tended also to increase in the subsoil at depths of 20–40 cm, except for the control treatment. The pattern of increase was irregular and suggests that spatial variations in ploughing depth

Fig. 4 Soil organic carbon (SOC) at the end of the growing season per treatment for soil depths 0–20 cm and 20–40 cm. *Lines between plots* are shown only for reasons of clarity



and slight variations in sampling depth, in addition to leaching, may have contributed to the apparent increasing SEP values at depths of 20–40 cm. Increases in SEP were largest in treatments providing P fertilizer at rates ≥ 105 kg P_2O_5 ha^{-1} $year^{-1}$. No increases were observed at depths of 40–60 cm (not shown).

Soil extractable K (SEK) ranged between about 70 mg kg^{-1} and 150 mg kg^{-1}, equivalent to 1.8–3.8 mmol kg^{-1}. Over time, SEK remained rather stable or tended to decrease slightly (Fig. 5), which contrasts with the highly negative K balances in all treatments but two (Table 2, Fig. 1). SEK was positively related to added stover and manure (Table 3). Subsoil (20–40 cm) SEK was, on average, 75 mg kg^{-1} and remained constant during the period (1997–2004) that K was analyzed (data not shown).

Discussion and conclusions

Long-term field experiments and deriving fertilization recommendations

This study was originally set-up to derive N fertilizer recommendations for maize under reduced tillage conditions, as a function of added stover and animal manure. Reduced tillage with direct seeding of maize in the soil without prior tillage in spring was introduced in the 1980s and 1990s because it is highly effective in minimizing wind erosion in spring (Cai et al. 2002; Wang et al. 2006). However, this practice necessitates the application of any stover, manure and fertilizers after harvest in autumn, because application in spring without tillage would lead to high risks of its being blown away by the incidental strong winds. The application of organic

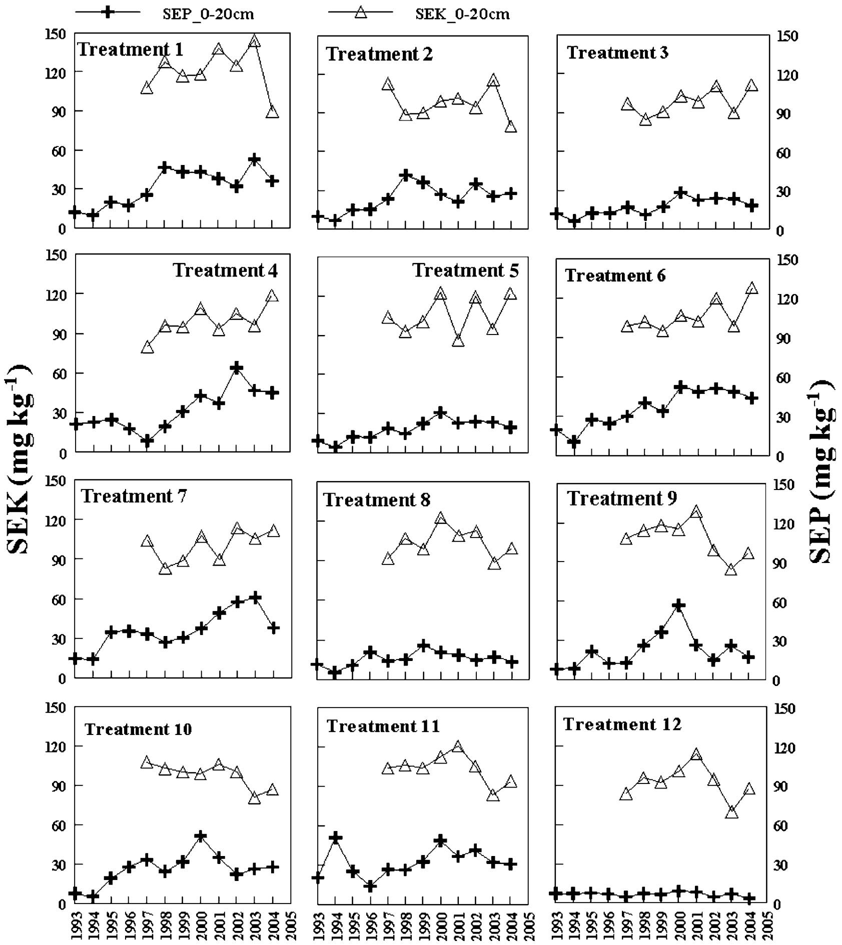


Fig. 5 Extractable soil P (SEP) and extractable soil K (SEK) in the topsoil (0–20 cm), per treatment at the end of the growing season. *Lines between plots* are shown only for reasons of clarity. Note that SEK analyses started in 1997

residues and fertilizers 6–7 months before seeding is only practicable when possible nutrient losses via run off, leaching and denitrification are negligible. Evidently, this reduced tillage practice creates a possible trade-off between decreased wind erosion and increased nutrient losses before the growing season. Nutrient losses during the winter season were assumed to be very small, because of the cold and dry weather. Results so far indeed suggest that N losses during the winter season are small (Wang et al. 1997; Wang and Cai 2003), and that the N recoveries from applied N fertilizer, stover and manure are relatively high, when applied in optimum ratio (Wang et al. 2007a).

Recommendation for N fertilizer should account for any other sources of N, including crop residues and animal manure. For the highest possible N use efficiency, other nutrients should not be limiting. Fertilizer P was applied in proportion to N fertilizer, but K (and other nutrients) was not considered, initially. In the attempt to increase grain yield in Southeast Asia, the prime focus has been on adding N fertilizer and, secondly, on adding P fertilizer, while K has received much less attention (Jin et al. 1999; Dobermann et al. 1996, 1998; Ladha et al. 2003; Fan et al. 2005; Hoa et al. 2006). This neglect of K has led to negative K balances (Fig. 1) and to declining yields over time (Wang et al. 2007a). Only two treatments (nos. 5 and 6, Table 2) had slightly positive K balances, due to the relatively large inputs of K via both stover (37 kg ha^{-1} year^{-1}) and manure (33 kg ha^{-1} year^{-1}). Adding stover and manure has been highly instrumental in supplying K, but also for supplying N and effective organic C to the soil (Fig. 2). Such multiple effects of animal manure and organic residues have greatly contributed to the worldwide increased and renewed interests in organic residues and manure (e.g., Schröder 2005; Zingore et al. 2006).

Annual variations in NPK and C balances and in SEN, P and K after harvest were large. These variations were mainly related to the large annual variations in the amounts of SWS and GSR, though small-scale soil variations may also have contributed to variations in SEN, SEP and SEK. The large fluctuations between years indicate that long-term measurements are needed for establishing reliable mean nutrient balances in rainfed cropping systems. The trend of decreasing balances (for treatments with negative balances) or increasing balances (for treatments with positive balances) with time was, in part, also related to decreasing SWS and GSR over time, as these contributed to a decrease in N, P and K uptakes (Wang et al. 2007a). This again emphasizes the need for long-term records, to be able to separate the effects of changes in GSR from increasing or decreasing nutrient deficiency due to changes in soil fertility level (Fan et al. 2005).

Soil organic matter

Soil organic matter is crucial to the sustainability of crop production, but there is an ongoing debate about the pros and cons of C sequestration in soils and about the minimum and optimum levels of SOC content (Feller and Beare 1997; Loveland and Webb 2003; Janssen and de Willigen 2006b; Janzen 2006. Reducing tillage and adding crop residues and animal manure is aimed at maintaining or increasing SOC (e.g., Franzluebbers 2002), and our results indicate indeed that SOC content was slightly increasing during the experimental period in the topsoil of various treatments (Fig. 4). However, the relationship between cumulative C balance and SOC content in the topsoil was weak ($R^2 = 0.4$–0.6) and depended on the decay coefficients chosen for the calculation of the C balances (Fig. 6). Linear regression coefficients ranged from 11×10^{-5} to 17×10^{-5}, indicating that 6,000 kg ha^{-1} to 9,000 kg ha^{-1} of effective organic C would be needed to increase the SOC content in the 0–20 cm layer by 1 g kg^{-1}. These amounts are 2–4 times larger than the amount of C in the topsoil represented by 1 g kg^{-1}, suggesting that our simple calculations greatly underestimated the decay of SOC. The results presented in Fig. 6 also allow the interpretation that a negative C balance leads to a decrease in SOC, (in treatments with little or no inputs of organic residues and NP fertilizer), while a positive C balance does not lead to a significant increase in SOC. However, the overall relationship in Fig. 6 tends to be asymptotic, with SOC tending to a maximum value between 16 g kg^{-1} and 17 g kg^{-1}. A SOC content of around 15 g kg^{-1} in the topsoil is above critical levels set for deterioration of soil physical properties and impairment of nutrient cycling mechanisms (Loveland and Webb 2003; Janssen and de Willigen 2006a, b; Janzen 2006). We conclude that there is no pressing need to further increase SOC content at the study site, judged from soil physical and agronomic points of view. A mean SOC content of 15 g kg^{-1} is also above the level of 'ideal soil fertility' for obtaining a target yield of 10 mg ha^{-1} at 'equilibrium' fertilization, where the required N input is equal to the N taken up by the harvested crop (Janssen and de Willigen 2006a).

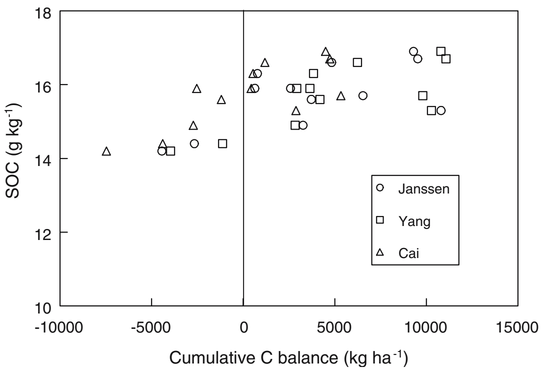


Fig. 6 Relationship between calculated cumulative C balance and SOC in the topsoil (0–20 cm), per treatment at the end of the experimental period. Cumulative C balances were calculated assuming simple first-order kinetics, using decay coefficients given by Janssen (1992), Yang (1996) and Cai (1996) (See text)

Soil fertility indices and nutrient balances

Classical soil fertility rating is based on relationships between soil test values and the crop response to added nutrients. The set-up of such rating systems requires extensive and long-term field testing, while the application in practice presumes that farmers do regular soil testing (Tisdale et al. 1985). Both requirements are not met in northern China, and there is an ongoing search for simple, effective and efficient recommendation systems that also account for possible environmental side effects (Zhang et al. 2005). Nutrient balances provide easy-to-obtain proxies for the potential environmental effects, but the actual impact of a balance cannot be understood properly without considering the actual soil fertility (Oborn et al. 2003; Janssen and de Willigen 2006a, b). This holds especially when residual effects are to be expected, as is the case with added manure and crop residues and P fertilizers in general.

Mean negative balances of N, P and K were observed in treatments 8 and 12, negative N and K balances combined with positive P balances in treatments 2, 3, 9 and 10, and negative N but positive P and K balances in treatment 5. Mean positive N and P balances, combined with negative K balances, were observed in treatments 1, 4, 7 and 11, while positive balances of N, P and K were found in treatment 6 only. This high number of combinations reflects the complexity of balanced fertilization (Janssen 1998).

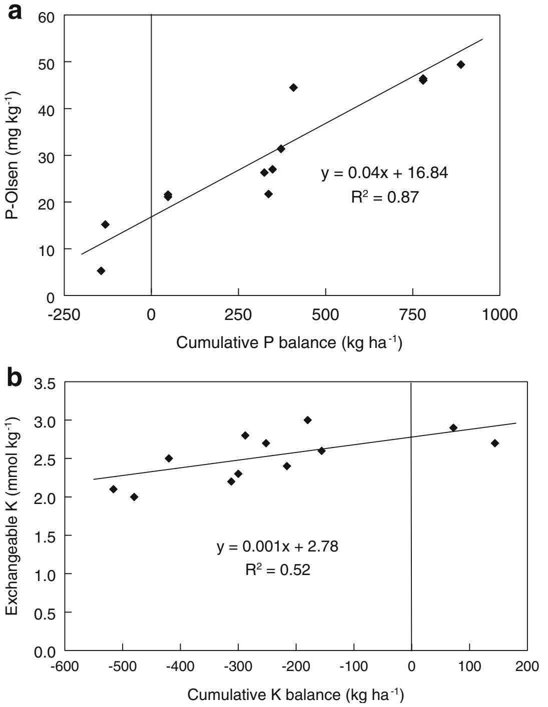


Fig. 7 Relationship between (**a**) the cumulative P balance and extractable soil P (P-Olsen) in the topsoil, and (**b**) the cumulative K balance and extractable soil K (exchangeable K) in the top soil, at the end of the experimental period per treatment

Negative N, P, K and C balances in various treatments coincided in most cases with decreases in SEN, P and K, and SOC content, indicating that the partial balances are a good proxy for evaluating the depletion of soil resources.

The relationship between cumulative P balances over the experimental period and mean SEP (P-Olsen) at the end of the experimental period is shown in Fig. 7a. Cumulative P balances ranged from −144 kg ha^{-1} to 888 kg ha^{-1}, and SEP from 5 mg kg^{-1} to 49 mg kg^{-1}. The regression coefficient of the linear relationships suggests that P-Olsen in the topsoil increases by 0.04 mg kg^{-1} when the P surplus is 1 kg ha^{-1}. If we assume that the surplus P is accumulated in the top 20 cm and that the bulk density of the topsoil is 1.2 mg m^{-3}, it follows that roughly 10% of the surplus P ends up as extractable P. Blake et al. (2003) found a higher recovery rate (10–40%) with 0.5 M $NaHCO_3$ (extracting agent used in P-Olsen method) in soils from long-term field experiments in Rothamsted, UK, even though they applied an initial extraction using resin strips. Richards et al. (1999) found that 13% of the increase in total soil P, following long-term P fertilization, remained soluble by the Olsen method. Differences between soils in the fraction of total soil P extractable by P-Olsen may be related to differences in sorption characteristics, P saturation index and soil pH. The relatively low P-Olsen extractability in the current experiment suggests that the P saturation index is low, but there are no experimental data available to substantiate this. Interestingly, treatments with manure and stover as main P source gave a stronger response in P-Olsen than treatments with P fertilizer as main P source. This is most clear for the treatments with a cumulative P surplus in the narrow range of 324–408 kg ha^{-1} with SEP ranging from 22–45 mg P kg^{-1}; here SEP was linearly related to the amount of P applied with manure. The positive effect of manure and stover on SEP also follows from the two treatments with a negative P balance (Fig. 7). Such positive effects of manure and crop residues on the extractability of soil P have been reported before for long-term manuring experiments (Olsen and Barber 1977) and tillage experiments (Hussain et al. 1999; Delgado et al. 2002).

The relationship between cumulative K balances over the experimental period and mean SEK (exchangeable K) at the end of the experimental period are shown in Fig. 7b. Cumulative K balances ranged from −516 kg ha^{-1} to 144 kg ha^{-1}, and SEK ranged from 2.0 mmol kg^{-1} to 3.0 mmol kg^{-1}. There was a weak linear relationship between cumulative K surplus and SEK; the small regression coefficient suggests that the exchangeable K pool in the soil is strongly buffered by recalcitrant K pools in the soils (c.f. Hoa et al. 2006). Mining of the soil for 12 consecutive years did not lead to a decrease in SEK. Conversely, SEK averaged over all treatments was slightly higher at the end than at the start of the experiment. Again, SEK values were higher in treatments with relatively large doses of manure and stover than in treatments with small doses of organic residues, suggesting that organic residues facilitated the transfer of K from recalcitrant K pools to the exchangeable K pool.

Janssen and de Willigen 2006b classified ratios of soil test values of N, P and K in terms of relative input requirements of N, P and K. Ratios of SOC (P-Olsen)$^{-1}$ <0.16 were classified as extremely N deficient, requiring only N input, and ratios of >1.37 were classified as P deficient, requiring inputs of N and P in a ratio <3.5. At the start of the experiment, the ratio SOC (P-Olsen)$^{-1}$ was 2.1, suggesting that the ratio for N and P inputs should be <3.5. The N:P ratios in fertilizer, manure and stover were 2.3, 5.5 and 17, respectively, indicating that NP fertilizer gave the best match. Janssen and de Willigen (2006b) classified ratios of SOC (exchangeable K)$^{-0.5}$ <4.6 as extremely N deficient and ratios of >12.9 as extremely K deficient, requiring only K input. At the start of the experiment, the ratio SOC (SEK)$^{-0.5}$ was 10.3, suggesting that the ratio of N and K inputs should be <1. The N:K ratios in manure and stover were 0.9 and 1.3, respectively, indicating that stover gave the best match. At the end of the experimental period ratios of SOC (SEP)$^{-1}$ ranged from 0.3 to 1.0 for the fertilizer and manure treatments to 2.7 for the control treatment (Table 4). Ratios of 0.3–1.0 have been classified as moderate N deficiency, requiring N:P input ratios of 3.5–7, while a ratio of 2.7 has been classified as P deficient, requiring N:P input ratios of <3.5 (Janssen and de Willigen 2006b). Ratios of SOC (SEK)$^{-0.5}$ were still high (range 9–10) in all treatments at the end of the experimental period, suggesting K deficiency. This classification is in line with the negative K balances observed in most treatments (Fig. 1).

Soil fertility and nutrient management in dryland farming

Soil fertility and nutrient management research are concerned ultimately with providing management information and viable options to farmers to make better decisions. The quality of this information is intimately tied to its value; it fails if it does not lead

Table 4 Mean soil fertility indices per treatment at the end of the experimental period. Treatments are arranged in order of increasing grain yield (see Table 1). Ratios of soil organic carbon (SOC) versus extractable soil phosphorus (SEP), and SOC versus extractable soil potassium (SEK) are explained in the text

Treatment	Treatment inputs, kg ha^{-1}			SEP mg kg^{-1}	SEK mmol kg^{-1}	SOCg kg^{-1}	SOC/SEP	SOC/(SEK)$^{0.5}$
	Fertilizer	Stover	Manure					
12	0	0	0	5.3	2.0	14.2	2.7	10.1
8	0	3000	1500	15.2	2.4	15.9	1.0	10.3
3	31	879	4500	21.1	2.6	15.9	0.8	9.9
10	105	0	1500	27.0	2.1	14.4	0.5	9.9
4	179	879	4500	46.0	2.7	16.3	0.4	9.9
5	31	5121	4500	21.6	2.7	16.9	0.8	10.2
7	210	3000	1500	49.4	2.8	15.6	0.3	9.4
2	105	3000	0	26.3	2.5	14.9	0.6	9.5
6	179	5121	4500	46.4	2.9	16.7	0.4	9.8
11	105	3000	3000	31.4	2.2	16.6	0.5	11.1
1	105	3000	6000	44.5	3.0	15.7	0.4	9.1
9	105	6000	1500	21.7	2.3	15.3	0.7	10.1

to economic and social (and environmental) benefits. Commonly, smallholder farmers in dryland areas do not invest in soil fertility, mainly because of the economic risk of such investments in drought-prone climates. There is often also a lack of information about the profitability of soil fertility investments and fertilizer use under diverse and risky environmental conditions, while such conditions require highly skilled management. This is also pertinent to northern China, even though fertilizers are heavily subsidized. In the attempts to increase crop production and to overcome the information gap, simple blanket fertilizer recommendations are promoted, where site-specific and weather-dependent management measures are needed. Tailoring of crop management practices to the expectations of the season in progress is what farmers in this region are doing, but this holds less for soil fertility and nutrient management.

Target soil fertility and target nutrient inputs should reflect target crop yields (Janssen and de Willigen 2006b), but how to answer this question for rainfed areas where 'target' maize yields may range from more than 10,000 in relatively wet years to <3,000 kg ha^{-1} in relatively dry years? Soil fertility and nutrient management should respond to such variable conditions, in a way commonly termed as 'response farming' (Stewart 1991). From economic and environmental points of view, it would be rather unwise to strive at high soil fertility levels under such conditions. Instead, soil fertility should be tailored to a level where losses of soil nutrients are minimal, while target yields for the relatively wet years can still be realized with proper doses of input nutrients. The 'ideal soil fertility level' for mean target yields of 7,000 kg ha^{-1} may be a proper target level, with P-Olsen values around 20 mg kg^{-1} and exchangeable K around 2 mmol kg^{-1}, and assuming a SOC content of 15 g kg^{-1}. The quantity of input nutrients should be tailored to target yields of ca. 10 mg ha^{-1}, but the application of N should be split, with a major portion being applied before seeding and a supplemental portion, dependent on rainfall expectation, applied at the 4–6 leaf stage (Schröder et al. 2000).

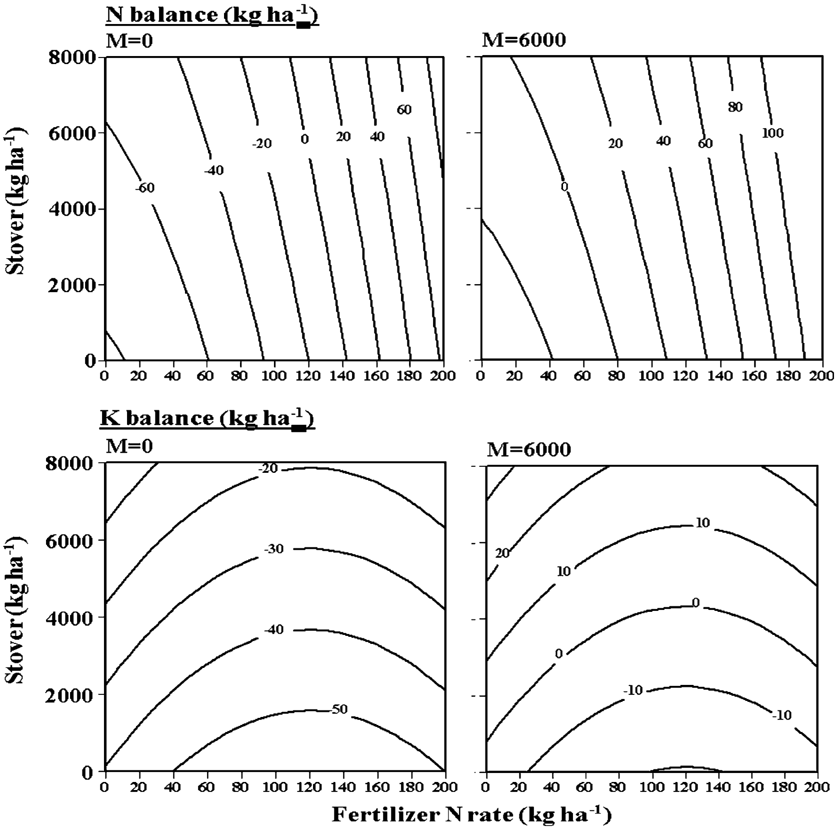


Fig. 8 Calculated relationships between added stover, manure and N, and partial N balances (*upper panels*) and K balances (*lower panels*) for mean GSR and SWS, using the equations presented in Table 3

As an example, and for average rainfall conditions, Fig. 8 presents N and K balances as functions of added N fertilizer, cattle manure and stover. Clearly, N balances are strongly related to N fertilizer input, while K balances are also related to stover and manure inputs. Neutral balances (input = output) relate to 'ideal soil fertility', i.e., the soil nutrients and input nutrients together satisfy the nutrient demand of the crop. Without manure, N fertilizer inputs should be in the range of 140–100 kg ha^{-1} for stover inputs in the range of 0–8,000 kg ha^{-1}. With 6,000 kg ha^{-1} of cattle manure as basal dressing, N fertilizer inputs should be in the range of 80–20 kg ha^{-1} for stover inputs in the range of 0–8,000 kg ha^{-1}.

Conclusions

Reduced tillage, combined with modest inputs of organic residues, maintained SOC content at the initial levels of 15 g kg^{-1} in the topsoil (0–20 cm) and at 11 g kg^{-1} in the subsoil (20–40 cm). Increased inputs of effective C only marginally increased SOC content in the topsoil. The available evidence indicated that there is no real prospect or need for increasing SOC contents beyond current levels.

Partial N, P and K balances were strongly related to added NP fertilizer, stover and animal manure, and to growing season rainfall. Most treatments had a positive P balance, which led to increases in extractable soil P (P-Olsen). However, only a fraction of the P added to the soil was extractable. Most treatments had negative K balances, but these negative K balances did not lead to a strong drop in exchangeable soil K. The rather weak relationship between K balances and exchangeable K indicated that the soil had a high K buffering capacity.

The analysis of nutrient balances and soil fertility indices revealed that nutrient inputs in most treatments were far from balanced. Balanced fertilization under conditions of variable rainfall is indeed highly complicated. The concept of 'ideal soil fertility level' is applicable in principle to variable rainfall conditions, but the definition of target yield and the partitioning of basal and supplemental N dressings need further examination. It is concluded that nutrient management should become an integral part of 'response farming' in this drought-prone area.

Acknowledgments The studies are part of the National Dryland Farming Key Projects of Science and Technical Supporting Programs/the National High-Tech Research and Development Programs of China ("863 Program") for the 8th, 9th, 10th and 11th Five-Year Plans (no. 2006AA100220/2006AA100220206) and the International Cooperation Project (2006DFB32180) financed by the Ministry of Science and Technology of China, and co-financed by China Scholarship Council, the National Natural Science Foundation of China (no. 40571151), the State Key Laboratory of Soil and Sustainable Agriculture at the Chinese Academy of Sciences, and Beijing Key Lab of Resources Environment and GIS at Capital Normal University. This paper was accomplished in cooperation with the Department of Soil Quality and the Farm Technology Group at Wageningen University.

References

Blake L, Johnston AE, Poulton PR, Goulding KWT (2003) Changes in soil phosphorus fractions following positive and negative phosphorus balances for long periods. Plant Soil 254:245–261

Cai DX (1996) Maintenance of soil organic matter balance in the farmland of dryland. In: Leng SL, Han SF (eds) The theory and technology of water-saving and yield-increasing for dryland crop in North China. Chinese Agricultural Science and Technology Press, pp 210–222 (in Chinese)

Cai DX, Wang XB, Zhang ZT, Gao XK, Zhang JQ (2002) Conservation tillage systems for spring corn in the semi-humid to arid areas of China. In: Stott DE, Mohtar RH, Steinhardt GC (eds) Sustaining the global farm. Selected papers from the 10th International Soil Conservation Organization meeting, pp 366–370

Delgado AA, Madrid A, Kasem S, Andreu L, del Campillo MC (2002) Phosphorus fertilizer recovery from calcareous soils amended with humic and fulvic acids. Plant Soil 245:277–286

Dobermann A, Sta Cruz PC, Cassman KG (1996) Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice systems I. Potassium uptake and K balance. Nutr Cycl Agroecosyst 46:1–10

Dobermann A, Cassman KG, Mamaril CP, Sheehy JE (1998) Management of phosphorus, potassium and sulfur in intensive, irrigated lowland rice. Field Crops Res 56:113–138

Duan L, Xie SD, Zhou ZP, Ye XM, Hao JM (2001) Calculation and mapping of critical loads for S, N and acidity in China. Water Air Soil Pollut 130:1199–1204

Fan TL, Stewart BA, Yong W, Luo JJ, Zhou GY (2005) Long-term fertilization effects on grain yield, water-use efficiency and soil fertility in the dryland of Loess Plateau in China. Agric Ecosyst Environ 106:313–329

Feller C, Beare MH (1997) Physical control of soil organic matter dynamics in the tropics. Geoderma 79:69–116

Franzluebbers AJ (2002) Soil organic matter stratification ratio as an indicator of soil quality. Soil Till Res 66: 95–106

Goodlass G, Halberg N, Verschuur G (2003) Input output accounting systems in the European community—an appraisal of their usefulness in raising awareness of environmental problems. Eur J Agron 20:17–24

Hoa NM, Janssen BH, Oenema O, Dobermann A (2006) Comparison of partial and complete soil K budgets under intensive rice cropping in the Mekong Delta, Vietnam. Agric Ecosyst Environ 116:121–131

Hussain I, Olson KR, Ebelhart SA (1999) Long-term effects on soil chemical properties and organic matter fractions. Soil Sci Soc Am J 63:1335–1341

ISS-CAS, Institute of Soil Science, Chinese Academy of Science (2003) Scientific data base. China Soil data base, http://www.soil.csdb.cn/ Last Updated: March, 2003. Institute of Soil Science, CAS, China

IUSS Working Group WRB (2006) World reference base for soil resources 2006. A framework for international classification, correlation and communication, 2nd edn. World Soil Resources Reports No. 103. FAO, Rome

Janssen BH (1992) Organic matter and soil fertility. Wageningen Agricultural University, Wageningen

Janssen BH (1998) Efficient use of nutrients: an art of balancing. Field Crops Res 56:197–201

Janssen BH, de Willigen P (2006a) Ideal and saturated soil fertility as bench marks in nutrient management. I Outline of the framework. Agric Ecosyst Environ 116:132–146

Janssen BH, de Willigen P (2006b) Ideal and saturated soil fertility as bench marks in nutrient management. II Interpretation of chemical soil tests in relation to ideal and saturated soil fertility. Agric Ecosyst Environ 116:147–155

Janzen HH (2006) The soil carbon dilemma: Shall we hoard it or use it? Soil Biol Biochem 38:419–424

Jin JY, Lin B, Zhang W (1999) Improving nutrient management for sustainable development of agriculture in China. In: Smaling EMA, Oenema O, Fresco LO (eds) Nutrient disequilibria in agroecosystems: concepts and case studies. CABI Publishing, Wallingford, UK, pp 157–174

Ju XT, Zhang FS, Bao XM, Römheld V, Roelcke M (2005) Utilization and management of organic wastes in Chinese agriculture: Past, present and perspectives. Sci China Ser C-Life Sci 48:965–979

Keeney DR, Nelson DW (1982) Nitrogen inorganic forms. In: Page AL, Miller RH, Keeney DR (eds) Methods of soil analysis. Agronomy monograph 9 part 2, 2nd edn. American Society of Agronomy, Madison Wisconsin, pp 643–698

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

Liu JG, Diamond J (2005) China's environment in a globalizing world. Nature 435:1179–1186

Liu XB, Liu JD, Xing BS, Herbert SJ, Meng K, Han XZ, Zhang XY (2005) Effects of long-term continuous cropping, tillage, and fertilization on soil organic carbon and nitrogen of black soils in China. Comm Soil Sci Plant Anal 36:1229–1239

Loveland P, Webb J (2003) Is there a critical level of organic matter in agricultural soils of temperate regions: a review. Soil Till Res 70:1–18

Oborn I, Edwards AC, Witter E, Oenema O, Ivarsson K, Withers PJA, Nilsson SI, Stinzing AR (2003) Element balances as a tool for sustainable nutrient management: a critical appraisal of their merits and limitations within an agronomic and environmental context. Eur J Agron 20:211–225

Olsen SR, Barber SA (1977) Effects of waste application on soil phosphorus and potassium. In: Elliot LF, et al (eds) Soils for management of organic wastes and waste waters. SSA, ASA, CSSA, Madison, USA, pp 197–215

Richards IR, Clayton CJ, Reeve AJK (1999) Effects of long-term fertilizer phosphorus application on soil and crop phosphorus and cadmium contents. J Agric Sci (Cambridge) 131:187–195

Rosegrant MW, Cai X (2001) Water scarcity and food security: alternative futures for the 21st century. Water Sci Tech 43:61–70

Rozella S, Huang J, Zhang L (1997) Poverty, population and environmental degradation in China. Food Pol 22: 229–251

SAS Institute (2004) SAS 9.1.2 Qualification Tools User's Guide, Cary, NC

Schröder JJ (2005) Revisiting the agronomic benefits of manure; a correct assessment and exploitation of its fertilizer value spares the environment. Bioresource Tech 96: 253–261

Schröder JJ, Neeteson JJ, Oenema O, Struik PC (2000) Does the crop or the soil indicate how to save nitrogen in maize production? Reviewing the state of the art. Field Crops Res 66:151–164

Stewart JL (1991) Principles and performance of response farming. In: Muchow RC, Bellamy JA (eds) Climatic risk in crop production: models and management for the semiarid tropics and subtropics. CAB International, Wallingford, UK

Tisdale SL, Nelson WL, Beaton JD (1985) Soil fertility and fertilizers, 4th edn. Macmillan, New York.

Wang XB, Cai DX (2003) Nitrogen uptake by corn and N recovery in grain in dry farmland. Agric Sci China 2003, 2(8):898–905

Wang XB, Cai DX, Zhang ZT (1997) Efficient use of N fertilizer in dry farmland. In: Proceedings of the 3rd annual national workshop of young agricultural scientists, China association of agriculture science societies. Chinese Agriculture Science and Technology Press, pp 415–423

Wang XB, Oenema O, Hoogmoed WB, Perdok UD, Cai DX (2006) Dust storm erosion and its impact on soil carbon and nitrogen losses in northern China. Catena 66: 221–227

Wang XB, Cai DX, Hoogmoed WB, Perdok UD, Oenema O (2007a) Crop residue, manure and fertilizer in dryland maize under reduced tillage in northern China: I grain yields and nutrient use efficiencies. Nutr Cycl Agroecosyst. doi:10.1007/s10705-007-9113-7

Wang XB, Cai DX, Perdok UD, Hoogmoed WB, Oenema O (2007b) Developments in conservation tillage in rainfed regions of North China. Soil Till Res 93:239–250

Westerman RL (eds) (1990) Soil testing and plant analysis, 3rd edn. SSSA Book Ser 3 SSSA, Madison, WI

Xu ZR (ed) (1988) The optimum regression designs in agricultural experiments. Heilongjiang Science and Technology Press, pp 216–238

Yang HS (1996) Modelling organic matter mineralization and exploring options for organic matter management in arable farming in northern China. Ph.D. thesis, Wageningen Agricultural University, The Netherlands, 159pp

Zhang F, Ma W, Zhang W, Fan M (2005) Nutrient management in China: from production system to food chain. In: Li CJ, Zhang FS, Doberman A, Hinsinger P, Lambers H, Li XL, Marschner P, Maene L, McGrath S, Oenema O, Peng SB, Rengel Z, Shen QR, Welch R, Von Wirén N, Yan XL, Zhu YG (eds) Plant nutrition for food security. Human Health and Environmental Protection, Beijing 2005, pp 13–15

Zhang JQ, Wang WS, Cai DX, Zhang MR, Wang WM (1984) Measurement of their ratios of grain, shoot, stubble and root biomass for wheat and other cereal crops. Ann Res Rep Soil Fertilizer Ins, CAAS, pp 113–115

Zebarth BJ, Paul JW, Van Kleeck R (1999) The effect of nitrogen management in agricultural production on water and air quality: evaluation on a regional scale. Agric Ecosyst Environ 72:35–52

Zingore S, Delve RJ, Nyamangara J, Giller KE (2006) Multiple benefits of manure: a key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms. In: Zingore S (ed) Exploring diversity within smallholder farming systems in Zimbabwe: nutrient use efficiencies and resource management strategies for crop production. Ph.D. thesis, Wageningen University, the Netherlands. pp.83–107