RESEARCH ARTICLE

Crop residue, manure and fertilizer in dryland maize under reduced tillage in northern China: I grain yields and nutrient use efficiencies

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Abstract The rapidly increasing population and associated quest for food and feed in China has led to increased soil cultivation and nitrogen (N) fertilizer use, and as a consequence to increased wind erosion and unbalanced crop nutrition. In the study presented here, we explored the long-term effects of various combinations of maize stover, cattle manure and nitrogen (N) and phosphorus (P) fertilizer applications on maize (*Zea mays* L.) yield and nutrient and water use efficiencies under reduced tillage practices. In a companion paper, we present the effects on nutrient balances and soil fertility characteristics. The ongoing factorial field trial was conducted at Shouyang Dryland Farming Experimental Station in northern China from 1993 onwards. The incomplete, determinant-optimal design comprised 12 treatments, including a control treatment, in duplicate. Grain yields and N, P, and potassium (K) uptakes and N, P and K use efficiencies were greatly influenced by the amount of rain during the growing season (GSR), and by soil water at sowing (SWS). There were highly significant interactions between GSR and added stover and manure, expressed in complex annual variations in grain yield and N, P and K use efficiencies. Annual mean grain yields ranged from 3,000 kg ha^{-1} to 10,000 kg ha^{-1} and treatment mean yields from 4,500 kg ha^{-1} to 7,000 kg ha^{-1}. Balanced combination of stover (3,000–6,000 kg), manure (1,500–6,000 kg) and N fertilizer (105 kg) gave the highest yield. Stover and manure were important for supplying K, but the effects differed greatly between years. Overall mean N recovery efficiency (NRE) ranged from 28% to 54%, depending on N source. NRE in wet years ranged from 50% to 90%. In conclusion, balanced combinations of stover, manure and NP fertilizer gave the highest yield and NRE. Reduced tillage with adding stover and manure in autumn prior to ploughing is effective in minimizing labor requirement and wind erosion. The potentials of split applications of N fertilizer, targeted to the need of the growing crop (response farming), should be explored to further increase the N use efficiency.

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Introduction

Fertilizer nitrogen (N) and phosphorus (P) uses have increased rapidly in China during the last two decades, in response to the increasing quest for food by the rapidly growing human population. On the lists of fertilizer production and consumption, China ranks number one, accounting for 22% and 25% of the world totals, respectively (FAO 2005). From the 1980s onwards, the rate of increase of fertilizer use has been larger than the rate of increase of food production, and the gap between the growth rates has continued to widen (Ye and Rozelle 1994). Fertilizer costs account for about 25% of the total annual expenses in crop production and for about 50% of total cost for input materials (seed, fertilizer, pesticides, machinery, irrigation), even though fertilizers are heavily subsidized (Lin et al. 1999; Ye and Rozelle 1994). The increasing use of N and P fertilizers and the neglect of manure and wastes as valuable resources of nutrients and soil organic matter (Ju et al. 2005; Yang 2006) have contributed to unbalanced fertilization, low fertilizer use efficiency, and to eutrophication of surface waters and contamination of the environment (Cao 1996; Cai et al. 2002; Bao et al. 2006; Ju et al. 2006).

The dryland areas of northern China are highly important for providing food and feed to the growing human and animal populations. Continuous maize (*Zea mays* L.) or wheat (*Triticum aestivum* L.), and wheat-maize rotations are the dominant cropping systems. Maize accounts for 22% of the total area of food crops, and 26% of the total food production in China (China Agricultural Yearbook 1999). Yields of maize and wheat vary greatly from year to year, mainly because of the variable (unpredictable) rainfall and wind erosion in spring (Wang et al. 2006). These effects are exaggerated by the current practices of removing crop residues from the field after harvest, to leave the ploughed soil bare during winter, and to plough the soil again in spring after fertilizer application. These practices commonly lead to soil drying and severe wind erosion in early spring. Erosion of fertile top soil, removal of crop residues (to feed animals and to be used as fuel for cooking with only partial return of manure and ashes to the cropped land) and burning of crop residues have led to nutrient depleted soils on various places (Rees et al. 1997; Cai et al. 2002; Peng et al. 2006).

Soil conservation and improved nutrient management practices are gaining interest of Chinese research and policy communities (Wang et al. 1999, 2001, 2003; Ju et al. 2005). There is a revival of the centuries-long tradition of recycling organic residues, but now combined with mineral fertilizers. For the humid areas of China, effects of combined applications of animal manure and inorganic fertilizers on soil fertility and crop yield have been reported by Lin and Lin (1985), Xie et al. (1987), and Liu et al. (1996). Long-term effects of combined applications of animal manure and mineral fertilizers in dryland areas have been examined by Fan et al. (2005a), Yang et al. (2004), and Zhen et al. (2006). A step further is to combine conservation tillage with improved nutrient management practices, including also the recycling of crop residues, because increasing amounts of crop residues are left in the field, especially in areas where fossil energy is used for cooking.

Reduced tillage was introduced in the study area in the early 1990s and it showed to be highly effective in decreasing soil drying and wind erosion (Wang et al. 2006). However, this practice required that fertilizers, crop residues and manure are applied in autumn prior to ploughing, approximately 6 months before maize is seeded. Applying fertilizers long before the crop growing season is only feasible in dry conditions where nutrient losses are minimal. The objective of our study is to optimize the combined application of NP fertilizers, maize stover and cattle manure under reduced tillage practices. We therefore assessed the long-term effects of these applications on maize grain yield and nutrient use efficiency. A companion paper (Wang et al. 2007) describes the effects of these combined applications on N, P and K balances, soil organic matter dynamics and soil fertility indices.

Materials and methods

Site description

The ongoing long-term field experiment started in 1992 at the Dryland Farming Experimental Station (Ministry of Agriculture) in Shouyang, Shanxi province in northern China (112°–113°E, 37°–38°N). 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 water and wind erosion in the past has led to the formation of a hilly landscape. The winter and spring season are dry and there are often strong winds. The dominant cropping system is continuous spring maize, which accounts for over 50% of the total area for crop production. Spring drought often is 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 a Calcaric-Fluvic Cambisol (ISS-CAS 2003; IUSS 2006). At the start of the experiment in 1992, soil pH was 7.9, and organic matter and N contents were 25.7 and 1.04 g kg^{-1}, respectively. Soil fertility level was low to medium, judged on the basis of P-Olsen (7.3 mg P kg^{-1}) and NH_4OAc extractable K (2.2 mmol K kg^{-1}) in the top 20 cm soil. To make the soil mineral N status spatially uniform and low, millet was grown without nutrient application in 1992, before the actual start of the experiment.

Experimental design

The experimental layout was a determinant-optimal (Xu 1988) 311A hybrid design, applying the response surface methodology (Roquemore 1976) with three factors, viz. NP fertilizer, maize stover and cattle manure. The experiment comprises 12 treatments, including a control treatment, in duplicate. Fertilizer NP (ratio N:P = 1:0.44) 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}. This experimental design allows the use of a minimal set of factors of the variance-covariance matrix and provides a maximal efficiency of the experiment. An important condition is that within the range of applications chosen, the optimum responses are found. The procedures of this design are explained in Khuri and Cornell (1987) and shown in Table 1. The corresponding statistical model is a quadratic equation of the form:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{11}X_1^2 + b_{22}X_2^2 + b_{33}X_3^2$$

(1)

where Y = grain yield or nutrient uptake, in kg ha^{-1}; X_1 = NP fertilizer, kg ha^{-1}; X_2 = stover, kg ha^{-1}; X_3 = manure, kg ha^{-1}; and b_0, b_1, b_2, b_3, b_{11}, b_{12}, b_{22}, b_{13}, b_{23}, b_{33} = coefficients.

Methods

Plots (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 (7% P) in a ratio of N to P of 1:0.44. Maize stover and cattle manure were obtained from local farms. The weighted mean contents of organic matter, total N, total P (as P) and total K were 75%, 0.63%, 0.039% and 0.72% for maize stover (ratio of N:P:K = 100:6:114) and 36%, 0.96%, 0.17% and 0.74% for cattle manure (ratio of N:P:K = 100:18:77), respectively. Maize stover (s), cattle manure (m) and fertilizers (f) 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 60 cm between rows and at 30 cm within the rows. Mean plant density was 55,555 per ha. Weeding was done manually twice during the growing season. Maize was harvested close to the ground using 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 crop residues were oven dried at 70°C and weighed. Harvest index (HI) was calculated as the ratio of grain to total aboveground biomass yield.

Grain and stover were analyzed for total N using the Kjeldahl method, total P using the H_2SO_4–$HClO_4$ method and total K using the HNO_3–$HClO_4$-flame photometry methods (Westerman 1990). Plant analyses of N and P started in 1993, those of K in 1997. Soil samples for moisture determination were taken at seeding and after harvest per plot. Each sample was a composite of three random 2-cm diameter cores per plot, taken at depths of 0–10, 10–20, 20–40, 40–60, 60–80, 80–100, 100–120, 120–140, 140–160, 160–180, 180–200 cm. The total volume of soil per layer

Table 1 Experiment treatments and description of the calculation method for design optimization

Treatment	Design matrix			Application rates (kg ha^{-1})		
	X1	X2	X3	Fert. N	Stover	Manure
1	0	0	2	105	3000	6000
2	0	0	−2	105	3000	0
3	−$\sqrt{2}$	−$\sqrt{2}$	1	31	879	4500
4	$\sqrt{2}$	−$\sqrt{2}$	1	179	879	4500
5	−$\sqrt{2}$	$\sqrt{2}$	1	31	5121	4500
6	$\sqrt{2}$	$\sqrt{2}$	1	179	5121	4500
7	2	0	−1	210	3000	1500
8	−2	0	−1	0	3000	1500
9	0	2	−1	105	6000	1500
10	0	−2	−1	105	0	1500
11	0	0	0	105	3000	3000
12 (Control)				0	0	0

Range	Code	Designed variable			Methods of calculation for design optimization		
		X1	X2	X3	X1 (fert. N)	X2 (stover)	X3 (manure)
Min.	−2	0	0	0	0	0	0
	−$\sqrt{2}$	31	879		105 + 52.5 × (−1.414) = 31	3000 + 1500 × (−1.414) = 879	
	−1			1500			3000 + 1500 × (−1) = 1500
Center	0	105	3000	3000	Z_{01} = (210 + 0)/2 = 105	Z_{02} = (6000 + 0)/2 = 3000	Z_{03} = (6000 + 0)/2 = 3000
	1			4500			3000 + 1500 × (1) = 4500
	$\sqrt{2}$	179	5121		105 + 52.5 × (1.414) = 179	3000 + 1500 × (1.414) = 5121	
Max.	2	210	6000	6000	210	6000	6000

Center: Z_{0i} = (Xi_{max} + Xi_{min})/2 (i = 1, 2, 3)

Distance: d_i = (Xi_{max} − Xi_{min})/($Xcode_{max}$ + |$Xcode_{min}$|)

d_1 = (210 − 0)/(2 + |−2|) = 52.5; d_2 = (6000 − 0)/(2 + |−2|) = 1500; d_3 = (6000 − 0)/(2 + |−2|) = 1500

Variable: Xi = Z_{0i} + d_i × Xcode

was mixed thoroughly, and subsamples were weighed before and after drying at 105°C.

Data processing and statistical analysis

Three indices for nutrient use efficiency were chosen, i.e. the additional grain yield per unit of added nutrient (agronomic efficiency, AE), the ratio of grain yield to aboveground nutrient uptake (internal utilization efficiency or physiological efficiency, PhE) and the apparent recovery efficiency (RE) of applied inputs (Novoa and Loomis 1981; Moll et al. 1982). AE was calculated as the increase in grain yield that resulted from added nutrients relative to the control treatment, in kg grain per kg N or P applied via fertilizer, stover and manure. The apparent recovery efficiency of applied N (NRE) or P (PRE) is defined as the percentage of added N or P that is recovered in aboveground plant biomass at the end of the cropping season. For N, the equations for AE, RE and PhE read as follows.

$$AE = (GY_i - GY_{ck})/(Nf + Ns + Nm)_i \qquad (2)$$

$$RE = 100 * (Nuptake\_i - Nuptake\_ck)/ \\ (Nf + Ns + Nm)\_i \qquad (3)$$

$$PhE = GY/Nuptake \qquad (4)$$

where GY_i = grain yield of treatment i, with i = 1–11, kg ha^{-1}; GY_{ck} = grain yield of the control treatment (treatment 12), kg ha^{-1}; $Nuptake_i$ = the N-uptake of treatment i, kg ha^{-1}; $Nuptake_{ck}$ = N-uptake of the control treatment, kg ha^{-1}; Nf_i = fertilizer N application of treatment i, kg ha^{-1}; Ns_i = amount of N in stover applied to treatment i, kg ha^{-1}; Nm_i = amount of N in manure applied to treatment i, kg ha^{-1}.

Apparent water use or apparent evapotranspiration (ET, in mm) was calculated from the change in soil water contents between the beginning of the growing season at seeding (SWS, in mm) and the end of the growing season at crop harvest (SWH, in mm) plus rainfall received during the growing season (GSR), viz.

$$ET = (SWS - SWH) + GSR \qquad (5)$$

Hence, we assumed that there were no losses via deep drainage and runoff during the growing season. Apparent water use efficiency (WUE, in kg ha^{-1} mm^{-1}) was calculated from GY and ET, according to.

$$WUE = GY/ET \qquad (6)$$

Statistical analyses were done using GLM, REG and RSREG procedures of the SAS Institute, Inc. (2004). The data were subjected to an analysis of variance using. the GLM procedure. The mean pairwise comparison was based on the DUNCAN test at the 0.05 probability level (at $P \leq 0.05$). Mean responses of grain yield (GY) and N, P and K uptakes to added NP fertilizer, maize stover and cattle manure were calculated using Eq. 1. In addition, stepwise multivariate regression analyses were carried out. Linear and nonlinear (parabolic) statistical models were fitted to describe the relationships between GY and nutrient uptake on the one hand and added nutrients via fertilizer, crop residues and manure applications and GSR and SWS on the other hand.

Results

Variation in rainfall and soil water

During the 12-year experimental period (1993–2004), annual rainfall ranged from 251 mm in the dry year 1997 to 675 mm in the wet year 1995. On average, rainfall during the growing season (GSR) accounted for 89% of the annual rainfall, indicating that the growing season for maize (May–October) is well
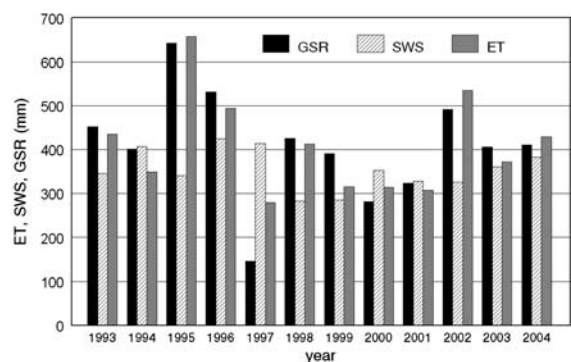

Fig. 1 Annual growing season rainfall (GSR), average amounts of soil water in the upper 2 m at sowing (SWS), and apparent water use (ET), in Shouyang during the experimental period 1993–2004

synchronized to the rainy season (June–September). However, annual variations in GSR were large, ranging from 146 mm in 1997 to 642 mm in 1995 (Fig. 1), and soil water shortage at sowing due to spring drought often occurred. Dry conditions at seeding impede seedling emergence and generally lead to low grain yield and nutrient uptake by maize (Cai et al. 1994). Apparent water use (ET) by maize ranged from a mean of 280 mm in 1997 to a mean of 660 mm in 1995 (Fig. 1).

Mean grain yield and N, P and K uptake

Mean grain yield and N, P and K uptakes in aboveground biomass per treatment are shown in Table 2. Note that treatments are in the order of increasing GY. The control (treatment 12) had the lowest GY and N, P and K uptakes, and treatment 9 (with f = 105, s = 6,000, and m = 1,500 kg ha^{-1}) the highest GY and also the highest N, P and K uptakes. Clearly, balanced combinations of NP fertilizer, stover and manure gave the highest mean yield, and the slight differences in GY between treatments 6, 11, 1 and 9 (the four treatments at the bottom of Table 2) were not statistically significant. Doubling NP fertilizer applications and halving the stover application (comparison of treatments 7 and 9) gave statistically significant lowering of GY, suggesting above optimal N application and below optimal K application in treatment 7 (see below).

Calculated mean responses of GY and N, P and K uptakes according to the regression equation pertinent to the design of the experiment (Eq. 1) are shown in Fig. 2. The regression coefficients for linear and quadratic effects of added NP fertilizer were all highly significant, but the mean effects of added manure and stover were not statistically significant (not shown). There were also no statistically significant interactions between added NP fertilizer, stover and manure in mean GY and N, P and K uptakes when using Eq. 1. Figure 2 shows that added stover and manure had larger relative effects on K uptake than on GY and N and P uptakes. Also, maximum K uptake was obtained at NP fertilizer application rates of about 100 kg per ha, while maximum GY and N and P uptakes were obtained at NP fertilizer application rates of 150–200 kg per ha, when no stover and/or manure was applied. When combined with stover

and manure, the required amounts of NP fertilizer for reaching maximum K uptake were larger than in the case of using only NP fertilizer. Conversely, the required amounts of NP fertilizer for obtaining maximum GY and N and P uptakes were smaller than in the case of single applications of NP fertilizer. These results indicate that the soil was responsive to N, P and K applications; a response to K was not foreseen at the start of the experiment.

Mean harvest index (HI) ranged from 47% to 52%, with highest values at intermediate GY (Table 2). Mean N recovery efficiency (NRE) in aboveground biomass ranged from 28% to 54%, and apparent N recovery in the grain (GNRE) from 18% to 35%. Variations between years within treatments were relatively large and only few treatments had statistically significant differences in NRE and GNRE. Mean P recovery efficiency (PRE) in aboveground biomass ranged from 10% to 85%, and GPRE from 8% to 62%. Highest NRE and PRE were in treatment 8 with combined applications of stover and manure, but without added NP fertilizer.

Mean apparent water use (ET) did not vary much among treatments (range 400–425 mm), and as a consequence, water use efficiency (WUE) varied greatly between treatments (Table 2). Lowest WUE (11 kg per ha per mm available water, or 1.1 kg ha^{-1} m^{-3}) was found in the control treatment and the highest WUE (19 kg per ha per mm available water, or 1.9 kg ha^{-1} m^{-3}) in treatment 9. This range (1.1–1.9 kg ha^{-1} m^{-3}) is similar to the range (1.1–2.0 kg ha^{-1} m^{-3}) measured in a long-term maize field experiment with various fertilization treatments in Gansu in China (Fan et al. 2005a).

Annual variations in grain yields

Annual variations in grain yield were large, ranging from about 3,000 in the dry year 1999 to more than 10,000 kg ha^{-1} in treatments with balanced fertilization in the wet years 1994, 1996 and 1998 (Fig. 3). Yields were related to GSR and also to soil water content at seeding (SWS). Grain yields in all treatments tended to decrease with time during the experimental period, especially in the control treatment (treatment 12). Differences in GY between the control treatment and the treatment with the second lowest GY (treatment 8 with f = 0, s = 3,000, m = 1,500 kg ha^{-1}) were absent during the first

Table 2 Effects of combined applications of NP fertilizer (F), maize stover (S) and manure (M) on grain yield (GY), Harvest Index (HI), uptake of N, P and K in aboveground biomass, N Agronomic Efficiency (NAE), Apparent N and P Recovery Efficiencies (NRE and PRE in aboveground biomass and GNRE and GPRE in grain), Water Use Efficiency (WUE) and Evapotranspiration (ET) per treatment, averaged over the whole experimental period (1993–2004)

Tmt.	F (kg ha⁻¹)	S (kg ha⁻¹)	M (kg ha⁻¹)	GY (1000 kg ha⁻¹)	HI (kg kg⁻¹)	N uptake (kg ha⁻¹)	P uptake (kg ha⁻¹)	K uptake (kg ha⁻¹)
12	0	0	0	4.6 E	0.47 D	84.3 E	11.7 E	40.0 E
8	0	3000	1500	5.1 D	0.47 CD	101.8 D	14.8 D	50.4 D
3	31	879	4500	5.8 C	0.50 ABCD	117.6 C	16.8 CD	50.0 D
10	105	0	1500	6.3 BC	0.51 AB	143.1 B	19.2 BC	54.1 CD
4	179	879	4500	6.4 B	0.51 AB	147.7 AB	21.3 AB	61.2 BC
5	31	5121	4500	6.4 B	0.52 A	128.1 C	18.8 BC	57.6 CD
7	210	3000	1500	6.5 B	0.52 A	150.9 AB	21.1 AB	55.6 CD
2	105	3000	0	6.5 B	0.50 ABC	146.3 AB	19.1 BC	54.2 CD
6	179	5121	4500	6.7 AB	0.50 ABCD	154.1 AB	22.0 A	63.6 BC
11	105	3000	3000	6.7 AB	0.49 ABCD	150.1 AB	20.8 AB	68.2 B
1	105	3000	6000	7.1 A	0.48 BCD	160.2 A	22.1 A	76.8 A
9	105	6000	1500	7.2 A	0.47 CD	158.4 A	22.1 A	78.3 A

Tmt.	NAE (kg kg⁻¹)	GNRE (%)	NRE (%)	GPRE (%)	PRE (%)	WUE (kg ha⁻¹ mm⁻¹)	ET (mm)
12	–	–	–	–	–	11.4 E	400.1 B
8	19.2 A	32.1 A	54.3 A	62.4 A	84.7 A	13.7 D	424.6 A
3	17.3 A	29.5 A	43.4 A	20.9 BC	25.2 BC	14.7 CD	410.5 AB
10	15.7 A	35.0 A	51.7 A	13.1 BCD	16.1 BCD	14.5 CD	400.9 B
4	8.4 B	18.4 B	28.0 B	9.3 CD	11.2 CD	15.9 BC	411.4 AB
5	17.4 A	30.9 A	41.2 AB	27.3 B	30.5 B	16.8 AB	403.2 B
7	8.3 B	18.4 B	27.6 B	8.2 CD	9.9 CD	16.9 AB	412.6 AB
2	15.9 A	33.9 A	50.1 A	13.2 BCD	16.2 BCD	15.4 BCD	413.1 AB
6	8.5 B	18.0 B	27.6 B	9.8 CD	11.8 BCD	17.0 AB	412.3 AB
11	14.7 A	28.6 A	43.4 A	14.8 BCD	17.5 BCD	16.2 BC	414.2 AB
1	14.1 AB	27.4 AB	41.5 AB	15.2 BCD	18.3 BCD	16.8 AB	417.4 AB
9	17.1 A	30.3 A	47.5 A	17.4 BC	20.6 BC	18.8 A	401.4 B

Data from 0 cm to 200 cm soil depth

Values with the same letter within a column are not significantly different at 5% level using the DUNCAN test of SAS

Fig. 2 Calculated average grain yield (GY), and plant N, P and K uptake responses to NP fertilizer (F), with and without maize stover (S: kg ha^{-1}) or manure (M: kg ha^{-1}) inputs during the period of 1993–2004 using RSREG statistical models (Eq. 1): (**a**) GY, (**b**) N uptake, (**c**) P uptake, (**d**) K uptake (see text). Note that Y-axes do not start at zero
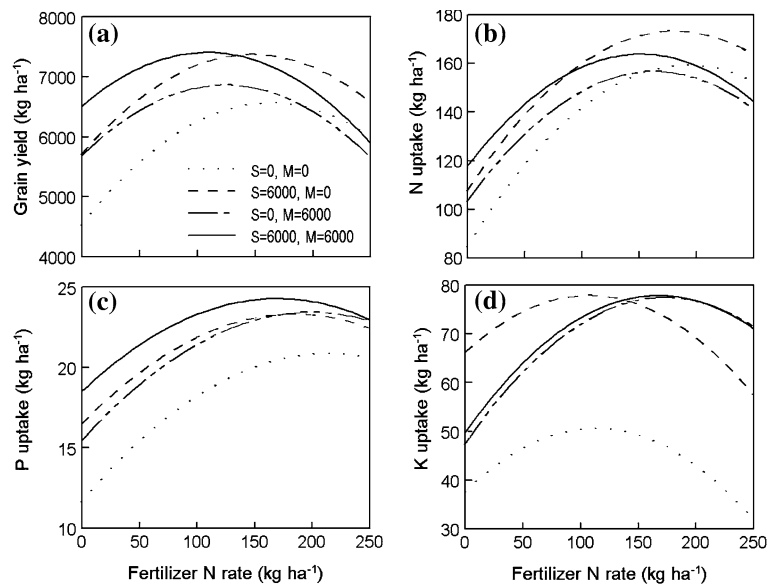
7 years (1993–1999), but were about 35% during the last 5 years (2000–2004) of the experiment.

Statistical analyses indicated that annual variations in GY per treatment were related to added fertilizer, stover and manure, and especially to GSR and SWS. Grain yield appeared highly sensitive to rainfall in July (at tasseling). Highest percentage of explained variance in GY (up to 88%) was obtained when the data set was split in wet (93, 94, 95, 96, 98) and dry years (97, 99, 00, 01, 02, 03, 04), and GY related to GSR and SWS, and added fertilizer, stover and manure. For dry years, GY was significantly related to SWS (but not to GSR) and to added fertilizer, stover and manure. In addition, there was a statistically significant interaction between added NP fertilizer and manure. For wet years, GY was significantly related to SWS and GSR (linearly and quadratic), and NP fertilizer, but not to added stover and manure (results not shown). These results would suggest that added manure and stover are important especially for dry years.

For the whole experimental period, differences in GY between treatments and between years were related to added fertilizer, stover and manure, and to SWS and the rainfall during the periods April–June, July and August–October (Fig. 3, Table 3). This model could also explain satisfactorily the decreasing trend in GY over the experimental period. Fan et al. (2005a, b) also observed decreasing trends in maize

(and wheat) yields in a long-term field experiment, which they ascribed to changing soil properties, decreasing trends in GSR and their interactions. The similar trends in measured and calculated GY (Fig. 3) suggest that the decreasing trend in GY in our experiment is mainly related to the changes in rainfall during the periods April–June, July and August–October. Overall, the statistical model tended to underestimate GY in wet years and overestimate GY in dry years. The large difference between measured and calculated GY in 2004 is possibly related to N losses prior and during the growing season and to diseases (head smut).

Water use efficiency (WUE) ranged from 4 kg ha^{-1} m^{-3} (equivalent to 40 kg ha^{-1} mm^{-1} of rainfall) in treatments with balanced nutrient inputs in dry 1997 to 0.65 kg ha^{-1} m^{-3} (6.5 kg ha^{-1} mm^{-1} of rainfall) for the control treatments in wet 1999, 2002 and 2004 (Fig. 4). There was a factor 5 difference in apparent water use (ET) between extremely dry 1997 and extremely wet 1995, while GY differed by only a factor of 1–2. Conversely, similar ET in 1994 and 2004 (about 430 mm) was accompanied with a factor 2–3 differences in GY. Evidently, there were additional factors involved in causing the large annual GY differences than simply GSR and SWS. The control treatments usually had the lowest WUE and treatments with balanced nutrient inputs the highest WUE in almost all years.
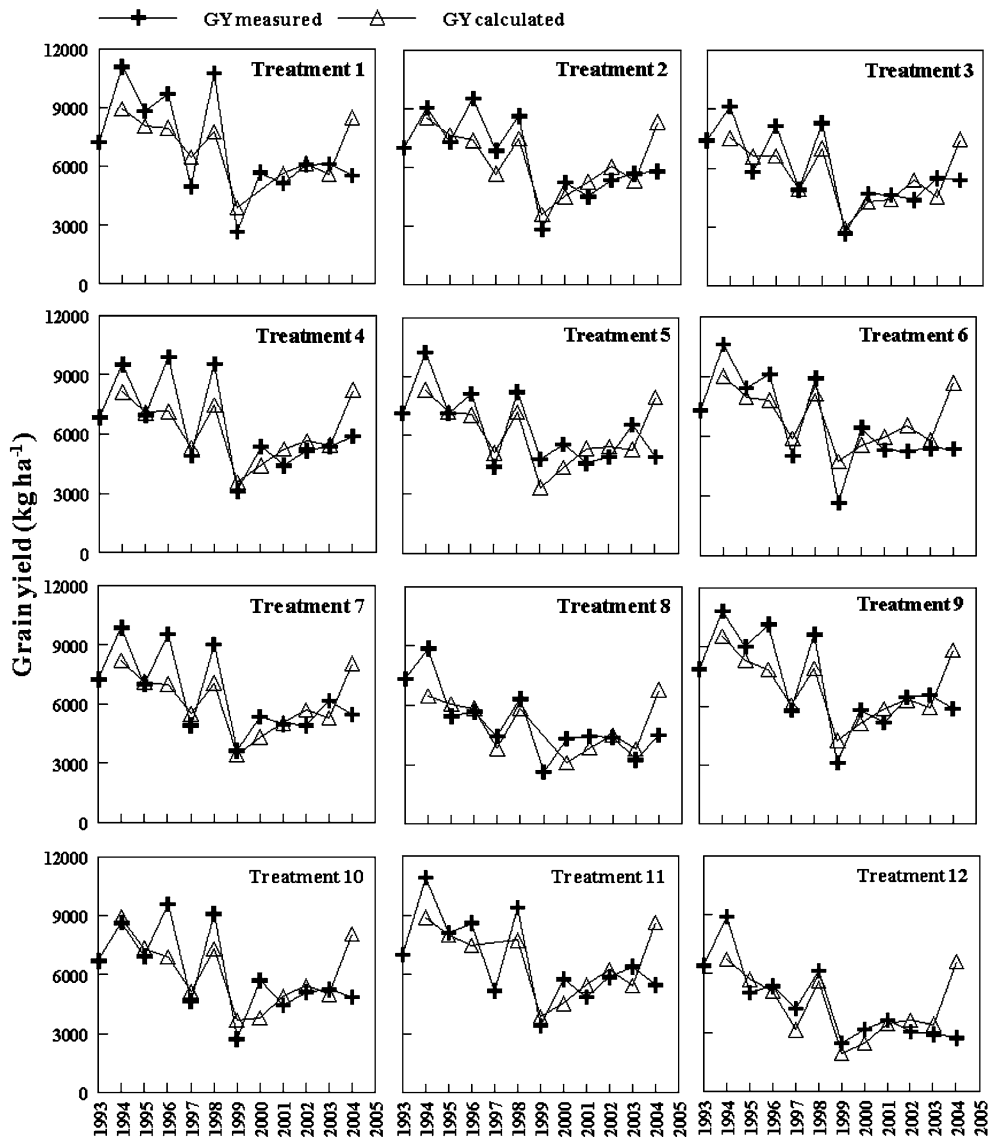
Fig. 3 Measured and calculated maize grain yields per treatment and year. Grain yields were calculated (GY-calculated) as function of added NP fertilizer (F), maize stover (S) and manure (M), and the amounts of soil water at seeding (SWS) and rainfall during the periods April–June (R(A–J)), July (R(J) and August– October (R(A–O), for the whole experimental period 1993–2004, according to GY = −5,140 + 24.9F + 0.14S + 0.07M + 7.13 R(A–J) + 23.5R(J) + 3.17R(A–O) + 15.4SWS − 0.09F^2 (see Table 3). Data from 0 cm to 200 cm soil depth. Yields for 1993 were not calculated because SWS data were missing

Annual variations in N, P and K uptakes in aboveground biomass

Uptake of N in aboveground biomass ranged from 100 kg ha^{-1} to 190 kg ha^{-1}, with uptake in wet years nearly twice as high as those in dry years. Uptake of N was related to added fertilizer and stover, but not to added manure, and SWS and rainfall in July and

August–October (Table 3). Splitting the data set in dry and wet years (see above) resulted in a higher percentage variance accounted for, and gave statistically significant effects of added stover and manure in dry years, but not in wet years (not shown). In addition, there was a statistically significant interaction between added NP fertilizer and manure in dry years but not in wet years.

Table 3 Coefficients of the regression models for grain yield (GY), N, P and K uptakes in aboveground biomass, and NRE, as function of NP fertilizer (both linear (Fertilizer) and quadratic (Fsq)), maize stover, and manure, soil water at sowing (SWS) and rainfall during the periods April–June (R(A–J)), July (R(J)) and August–October (R(A–O)), for the whole experimental period 1993–2004

Dependent Variable	Param.[a]	Intercept	Fertilizer	Stover	Manure	R(A–J)	R(J)	R(A–O)	SWS	Fsq
GY	PE	−5140	24.9	0.14	0.07	7.13	23.5	3.17	15.4	−0.09
$R^2 = 0.58$	SE	1213	6.4	0.07	0.07	3.39	2.71	1.47	2.80	0.03
$N = 129$	tValue	−4.24	3.9	2.01	1.0	2.1	8.70	2.16	5.51	−3.02
	Pr > |t|	<0.001	0.001	0.047	0.32	0.04	<0.001	0.03	<0.001	0.003
N uptake	PE	−24.6	0.79	0.003	0.001	−0.001	0.36	0.08	0.14	−0.003
$R^2 = 0.48$	SE	26.6	0.14	0.001	0.002	0.07	0.06	0.03	0.06	0.001
$N = 129$	tValue	−0.93	5.68	1.75	0.91	−0.02	6.12	2.49	2.29	−3.95
	Pr > |t|	0.36	<0.001	0.08	0.36	0.99	<0.001	0.01	0.02	0.001
P uptake	PE	−16.8	0.10	0.0005	0.000	−0.05	0.11	0.01	0.05	−0.0003
$R^2 = 0.58$	SE	4.54	0.02	0.000	0.000	0.01	0.01	0.006	0.01	0.000
$N = 128$	tValue	−3.69	4.06	1.83	1.57	−4.15	10.6	2.59	5.16	−2.67
	Pr > |t|	0.001	<0.001	0.07	0.12	<0.001	<0.001	0.01	<0.001	0.009
K uptake	PE	5.46	0.29	0.002	0.001	−0.04	0.30	0.04	−0.003	−0.001
$R^2 = 0.76$	SE	20.2	0.05	0.001	0.001	0.03	0.04	0.03	0.04	0.0003
$N = 93$	tValue	0.27	5.37	4.11	2.05	−1.29	8.59	1.01	−0.08	−4.72
	Pr > |t|	0.79	<0.001	<0.001	0.04	0.20	<0.001	0.31	0.94	<0.001
NRE	PE	29.7	0.05	−0.001	−0.003	0.002	0.09	0.07	0.03	−0.001
$R^2 = 0.21$	SE	19.6	0.11	0.001	0.001	0.05	0.04	0.02	0.04	0.000
$N = 117$	tValue	1.52	0.44	−0.92	−2.40	0.04	2.02	2.97	0.74	−1.72
	Pr > |t|	0.13	0.66	0.36	0.018	0.97	0.045	0.004	0.46	0.089

Data from 0 cm to 200 cm soil depth

[a] PE = Parameter Estimate; SE = Standard Error; Pr = probability-value (P-value)

Uptake of P in aboveground biomass ranged from 8 kg ha^{-1} to 32 kg ha^{-1}, with the highest values in wet years. Uptake of P was related to added fertilizer and stover, but not to added manure, and SWS and rainfall in April–June, July and August–October (Table 3). Again, splitting the data set in dry and wet years resulted in a higher percentage variance accounted for, and gave statistically significant effects of added stover and manure in dry years, but not in wet years (not shown). In addition, there was a statistically significant interaction between added NP fertilizer and manure in dry years but not in wet years.

Uptake of K in aboveground biomass ranged from 50 kg ha^{-1} to 90 kg ha^{-1}, and was statistically significant related to added fertilizer, stover and manure, and to rainfall in July (Table 3). The positive effects of manure and stover on K uptake, suggests indeed that stover and manure were important for supplying K to maize. Percentage variance accounted for was much higher for K uptake than for N and P uptake, but it should be noted that K uptake was not determined in 1993–1996. Splitting the dataset in dry and wet years did not increase the percentage variance accounted for.

Relationships between GY and N, P and K uptakes are shown in Fig. 5. On average 40–50 kg of grain was produced per kg N taken up in aboveground biomass (range 24–80). Highest PhE was in the control treatment and in productive years 1994, 1996, 1998, 2003. For N (Fig. 5a, b), PhE (GY/Nuptake) was relatively low in 1999 (about 30 kg kg^{-1}). For P, PhE ranged from 160 kg in 1999 and 2004 to 800 kg in 2002. There were no clear patterns between treatments, indicating that climate had a much stronger effect than treatments on the PPhE
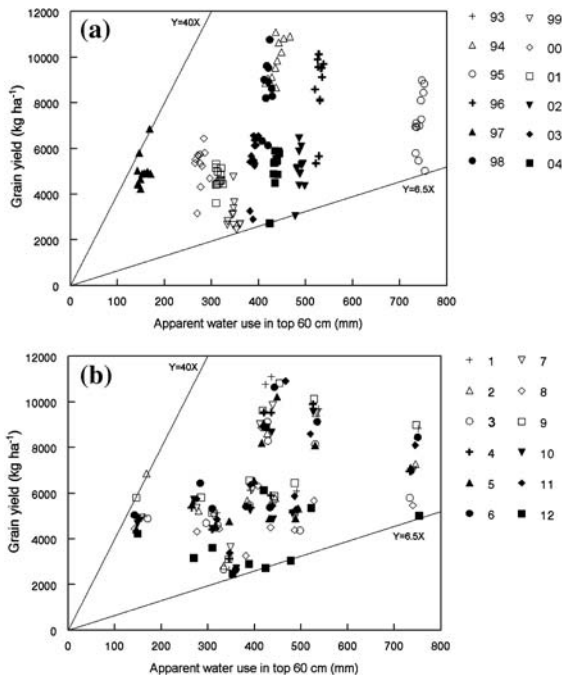
Fig. 4 Relationships between grain yield and apparent water use for all experimental years (**a**) and treatments (**b**). The lines $Y = 6.5X$ and $Y = 40X$ indicate extreme low and high water use efficiency, respectively, and are meant for comparison. Data from 0 cm to 60 cm soil depth

(Fig. 5c, d). For K, PhE ranged from 44 kg to 60 kg in 1999 and 2004 to 120–150 kg in 2003. On average, treatment 2 (f = 105, s = 3,000, m = 0 kg ha^{-1}) had the highest KPhE, but patterns were not consistent over years. Also for K, climate had a stronger effect than treatments on PhE (Fig. 5e, f).

Ratios of P uptake to N uptake in aboveground biomass ranged from 0.06 to 0.3 (equivalent to N/P ratios of 4 to 16 (Fig. 6)). Ratio of N/P was lowest in 2004 and highest in 2002. There were no clear and consistent patterns in N/P ratios between treatments. Ratios of K uptake to N uptake in aboveground biomass ranged from 0.3 to 1.0 (equivalent to N/K ratios of 1 to 3.6). Ratio of N/K was lowest in 2004 and highest in 2000. There were no clear and consistent patterns in N/K ratios between treatments (Fig. 6).

Apparent N recovery efficiency (NRE) was related to added manure and fertilizer (linear and quadratic effects, respectively) and to rainfall in July and August to October, but the percentage variance accounted for was small (Table 3). The same holds

for PRE (data not shown). Mean NRE ranged from about 25% in the dry years 1997 and 1999 to 70–80% in the wet years 1996 and 1998. Mean PRE ranged from about 15% in the dry years 1997 and 1999 to 30–40% in the wet year 1996 and 1998. Splitting the data set in dry and wet years (see above) resulted in a much higher percentage variance accounted for, and showed statistically significant effects of fertilizer and manure in dry years, and of fertilizer and stover in wet years (not shown). Also, there were statistically significant effects of fertilizer and manure on PRE in both dry and wet years. In addition, there was a statistically significant interaction between NP fertilizer and manure in both dry and wet years (not shown).

Discussion and conclusions

Grain yields of spring maize in drylands of northern China were greatly influenced by SWS and GSR. Differences between years in mean GY were in the order of 200–300% (e.g. between 1994 and 2004), and these differences were mainly related to SWS and GSR. In addition, GY was limited by the availability of nutrients, especially N, but likely also P and K. Added NP fertilizer, maize stover and cattle manure increased GY and N, P and K uptake in aboveground biomass, but effects of maize stover and cattle manure were not statistically significant in all years. Balanced combination of NP fertilizer, maize stover and cattle manure gave the highest yield. Averaged over the 12-year experimental period, a balanced combination of NP fertilizer, maize stover and cattle manure (treatment 9) increased GY by 60% relative to the control treatment. Clearly, fertilization effects were smaller than rainfall effects.

The difference in GY between the control treatment and the treatments with balanced combinations of NP fertilizer, stover and manure tended to increase over time, mainly because GY of the control treatment declined during the experimental period, due to nutrient depletion of the soil. Yields of other treatments also tended to decline during the experimental period, but this decline could be ascribed to changes in the amounts and distribution of rainfall over the growing season (Table 3, Fig. 3). Grain yields in some years may also have been affected by diseases (mainly head smut). Decreasing GSR, soil
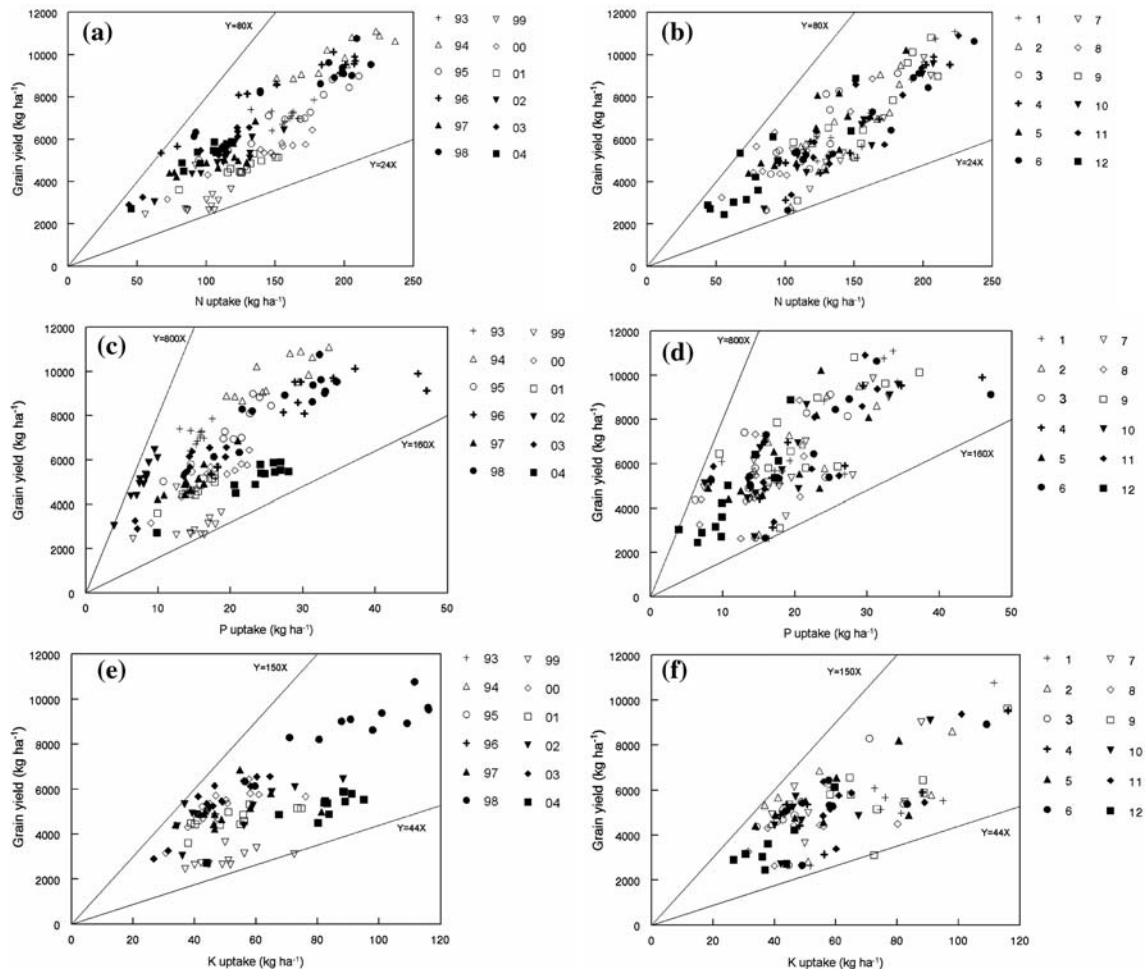
Fig. 5 Relationships between grain yield and N uptake for all experimental years (**a**) and treatments (**b**). Relationships between grain yield and P uptake for all experimental years (**c**) and treatments (**d**). Relationships between grain yield and K uptake for all experimental years (**e**) and treatments (**f**). The two lines within each graph approximate maximum dilution (high physiological nutrient use efficiency (PhE); upper line) and maximum accumulation (low physiological nutrient use efficiency; lower line)

nutrient depletion and diseases have been identified as major causes for declining yields of continuous spring maize cropping systems in northern China (Li et al. 2003; Bai et al. 2006).

Water limited grain production

Water use efficiency (WUE) averaged over the 12-year period ranged from 1.1 for the control treatment to 1.9 kg ha^{-1} m^{-3} for treatments with balanced additions of NP fertilizer, stover and manure (Table 2). These values are common for

non-irrigated maize production and clearly show that balanced fertilization increases the efficiency of water use (Van Keulen and van Laar 1986; Van Keulen and Seligman 1987; Fan et al. 2005a). Differences in WUE were much larger between years than between treatments (Fig. 4). Even at similar apparent water use, there were large differences in GY and hence in WUE. Some of these differences may be attributed to differences in maize variety, as different varieties were used for the periods 1993–1997, 1998 and 1999–2004. A major factor explaining differences in mean WUE between
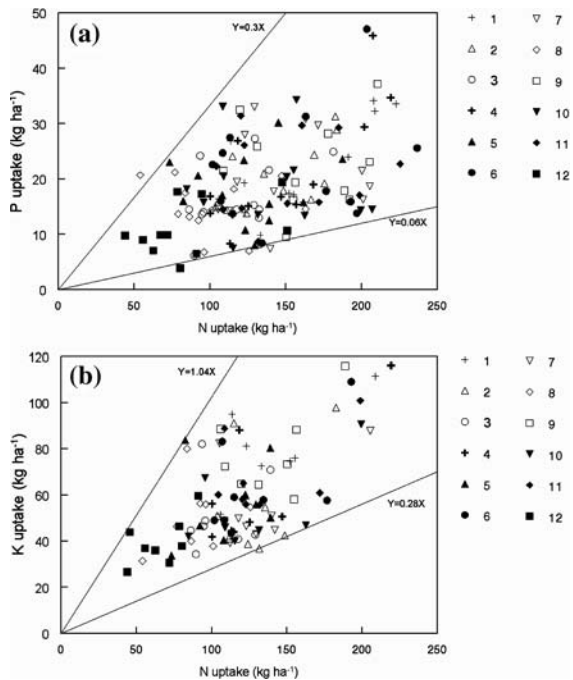
Fig. 6 Relationships between P uptake and N uptake (**a**) and between K uptake and N uptake (**b**) for all treatments. The lines within the graphs indicate extreme high (upper lines) and extreme low (lower lines) ratios of P:N (**a**) and K:N (**b**) in the aboveground biomass at harvest

years is the distribution of the rainfall over the growing season. Our results indicate that the amount of soil water at seeding (SWS) and the amount of rainfall during tasseling, commonly in July, are highly critical (Table 3). A third possible factor explaining differences in mean WUE between years is related to N losses and low N use efficiency. For example, the low WUE in 2004 (Fig. 4) is accompanied by low N/P and low N/K ratios (Fig. 6) and relatively high N use efficiency (Fig. 5a, b). This may suggest that N uptake was low because soil N was lost prior to or during the growing season. Alternatively, diseases may have (also) played a role. We recall that NP fertilizer, stover and manure were applied in autumn; late season rainfall and rainfall in winter and spring may have contributed to N losses via leaching and denitrification (Cai et al. 2002; Mosier 2002). Evidently, high SWS is beneficial from the view-point of germination and early growth of maize (Cai et al. 1994), but on the other hand may also contribute to N losses and low N use efficiency and thereby to low WUE.

Nutrient limited grain production

Balanced combinations of NP fertilizer, stover and manure gave higher GY than additions of NP fertilizer alone, at all levels of NP (Table 2, Fig. 2), suggesting that the effects of manure and especially stover were additional to the effects of NP fertilizer. Results presented in Table 3 and Figs. 2 and 5 show that stover and manure increased K uptake. Treatments with relatively large applications of NP fertilizers and low application rates of stover and manure had relatively high N/K ratio in the above-ground biomass (Fig. 6), indicating unbalanced supply of N and K. Deficiency of K was not foreseen at the start of the experiment in 1993, and analyses of K in biomass only started in 1997. Our results suggest that 'the stover effect' likely was a 'K effect'. Deficiency of K in crop production usually appears following increases in NP fertilizer applications and decreases in the use of organic fertilizers (Lin et al. 1999; Ju et al. 2005). Intensification of crop production, in combination with unbalanced fertilization, has already resulted in depletion of K in soils over large areas in China (Jin et al. 1999), India (Hasan 2002) and other countries in South-East Asia (Ladha et al. 2003; Hoa et al. 2006).

Maize GY responded to N and K applications and possibly also to P application. However, the effects of N and P were confounded because N and P applications were combined in all treatments. The response to N also follows from the relatively high PhE for N in the control treatment, which ranged from 40 kg to 80 kg grain per kg N taken up (Fig. 5a, b). The higher value is close to 'maximum dilution', which is indicative for shortage of N (Janssen et al. 1990; Janssen and de Willigen 2006). For K, PhE in the control treatment ranged from 40 kg to 120 kg grain per kg K taken up (Fig. 5e, f), and for P, PhE ranged from 160 kg and 800 kg grain per kg P taken up (Fig. 5c, d). Such wide ranges reflect variations between maximum dilution and maximum accumulation of K and P in the aboveground biomass (Janssen et al. 1990). The annual variations in PhE for P and K were related to the distribution of rainfall over the growing season. For both P and K, differences in PhE were smaller between treatments than between annual means, suggesting that GSR had much stronger effects on the K and P use efficiencies than NP fertilizer, stover and manure.

Fertilizers, stover and manure were applied in autumn after harvest of the crop, just before ploughing, and about 6 months before seeding. This practice was adopted to reduce wind erosion and soil drying in spring and also to minimize labor requirement (Cai et al. 1994; Wang et al. 2006). The trade-off is that added nutrients are present in the soil for a long time and thus will be more susceptible to losses. Mean apparent N recoveries (NRE) were in the range of 30–55%, which are common values for rainfed maize (Balashubramanian et al. 2004; Krupnik et al. 2004), suggesting indeed that N losses were not excessive. In years with a favorable rainfall distribution, NRE ranged from 50% to 90%. However, NRE values in treatments with stover and manure were positively affected by addition of K, especially during the second half of the experimental period when GY and N uptake of the control treatment had declined to relatively low values. We conclude that adding stover and manure in autumn just before ploughing, combined with direct drilling of maize seeds in spring, is a proper way of minimizing wind erosion and labor requirement, while crop yield and N use efficiency can still be relatively high. The experiment does not allow making a conclusion about the possible superiority of reduced tillage over conventional tillage practices as regards GY and nutrient use efficiencies.

Interactions between NP fertilizer, stover and rainfall in some years may point at temporary immobilization of N during the decomposition of stover, which has a high C/N ratio. Adding stover and N fertilizer simultaneously may temporary lock up mineral N in soil organic matter and thereby circumvent its possible loss from soil by leaching and denitrification, and its uptake by plant roots. This temporary immobilization of N in autumn and its partial mineralization during the growing season may have contributed to positive effects of stover application and also to the positive effects of combined applications of N fertilizer, stover and manure (Kramer et al. 2002). Split application of N fertilizer is a well-established management strategy to improve the N use efficiency of cereal crops (e.g., Schröder et al. 2000; Pattey et al. 2001; Angás et al. 2006). It is recommended to apply about half or two-thirds of the recommended total N dose at sowing and the supplement after emergence of the crop. The supplemental N should depend on rainfall conditions and the N status of the soil or crop (Schröder et al. 2000),

and in dry years, supplemental N should not be applied (Angás et al. 2006). When applied under the conditions of Shouyang, the first N dressing (up to 100 kg ha^{-1}, depending on stover and manure applications) should be applied after harvest (before ploughing), as in the current experiment. A possible second N dressing (up to 50 kg ha^{-1}) may be applied at the 4–6 leaves stage, depending on early season rainfall and the N status of the soil (Schröder et al. 2000; Dobermann and Cassman 2002). The feasibility of such split application technology in practice needs to be tested further. Evidently, split application will increase labor requirement, but can also contribute to further increasing N use efficiency.

Conclusions

Traditional Chinese farming was based on efficient utilization and recycling of natural resources. The increasing quest for food by the growing human population led to an increase of N (and P) fertilizer use, unbalanced nutrition and decreasing resource use efficiency. The results of this long-term field experiment show that applications of stover and manure at levels which can be realized on a farm can contribute to increase the use efficiency of N fertilizer.

Grain yield and N, P and K use efficiencies of rainfed maize were strongly related to rainfall and to soil water at seeding. The huge annual variations in physiological N, P and K use efficiencies indicate that there is scope for improvement of fertilizer use efficiency by split application.

The design of this field experiment was meant to provide the most effective and efficient way to balanced fertilization. There were three nutrient sources (NP fertilizer, stover and manure), each applied at five rates, and these were combined in an incomplete factorial design of 12 treatments only. The statistical model pertinent to the design was able to describe the mean responses of NP fertilizer, stover and manure reasonably well. This design has proven to be efficient for experiments with nutrient inputs. However, nutrient management under rainfed conditions requires rainfall to be taken into account in a dynamic approach (see also Wang et al. 2007) to explain the strong interactions between GSR and the effects of NP fertilizer, stover and manure. The feasibility and adoptability by farmers of split applications of N fertilizer combined with soil and/or plant analyses should be tested in practice.

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