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RESEACH ARTICLE

Crop response of aerobic rice and winter wheat to nitrogen, phosphorus and potassium in a double cropping system

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Abstract In the aerobic rice system, adapted rice cultivars are grown in non-flooded moist soil. Aerobic rice may be suitable for double cropping with winter wheat in the Huai River Basin, northern China plain. Field experiments in 2005 and 2006 were conducted to study the response of aerobic rice and winter wheat to sequential rates of nitrogen (N), phosphorus (P) and potassium (K) in aerobic rice—winter wheat (AR-WW) and winter wheat—aerobic rice (WW-AR) cropping sequences. Fertilizer treatments consisted of a complete NPK dose, a PK dose (N omission), a NK dose (P omission), a NP dose (K omission), and a control with no fertilizer input. Grain yields of crops with a complete NPK dose ranged from 3.7 to 3.8 t ha^{-1} and from 6.6 to 7.1 for aerobic rice' and 'winter wheat', respectively. N omissions caused yield reductions ranging from 0.5 to 0.8 t ha^{-1} and from 1.6 to 4.3 t ha^{-1} for rice and wheat, respectively. A single omission of P or K did not reduce rice and wheat yields, but a cumulative omission of P or K in a double cropping system significantly reduced wheat yields by 1.2–1.6 t ha^{-1}. N, P and K uptake of both crops were significantly influenced by fertilizer applications and indigenous soil nutrient supply. Nutrient omissions in a preceding crop reduced plant N and K contents and uptake additionally to direct effects of the fertilizer treatments in wheat, but not in rice. Apparent nutrient recoveries (ANR) differed strongly between 'aerobic rice' and 'winter wheat'; in rice: for N it ranged from 0.30 to 0.32, for P from 0.01 to 0.06, and for K from 0.03 to 0.19 and in wheat: for N from 0.49 to 0.71, for P from 0.09 to 0.15, and for K from 0.26 to 0.31. Further improvements of crop productivity as well as nutrient-use efficiencies, should be brought about by developing cropping systems, by an appropriate choice of adapted cultivars, by a site- and time-specific fertilizer management and by eliminating other yield-limiting factors. It is concluded that nutrient recommendations should not be based on the yield response of single crops only, but also on the after-effects on nutrient availability for succeeding crops. A whole cropping system approach is needed.

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Introduction

Rice is the most common staple food for the majority of people on Earth (Maclean et al. 2002). It is mostly grown under flooded conditions and consumes up to 43% of the world's developed irrigation resources (Bouman et al. 2007a). However, irrigation water for agriculture is becoming increasingly scarce, and it is estimated that, by 2025, 15–20 million ha of irrigated rice will suffer some degree of water scarcity (Tuong and Bouman 2003). Water shortage urges the development of water-saving technologies in rice production, such as alternate wetting and drying, non-flooded mulching cultivation, and aerobic cultivation (Bouman et al. 2007a; Belder et al. 2007, 2005; Tao et al. 2006; Liu et al. 2005). In aerobic rice systems, especially adapted cultivars are direct seeded in non-flooded and non-puddled soil and supplementary irrigation is applied only to keep the soil moist but not saturated. Compared with flooded lowland rice, aerobic rice systems can reduce water use by as much as 50% while realizing yields of up to 6 t ha^{-1} under optimum conditions (Bouman et al. 2007a, b; Yang et al. 2005; Wang et al. 2002).

As the severity of water scarcity increases, the system of aerobic rice becomes attractive for many areas of China. Wang et al. (2002) reported that the target areas for aerobic rice are regions where irrigation water is becoming too scarce to continue growing lowland rice, and regions with relatively favorable rainfall that is sufficient and reliable enough to grow upland crops such as maize or soybean. For example, in the Huai river basin in northern China, some 20 years ago the main crops were winter wheat and lowland rice (in summer); however, farmers started replacing lowland rice with crops such as maize, soybean, and cotton, because of increasing shortage of water (Tong et al. 2003). Despite the general water scarcity in this area, high rainfall and severe water-logging often occurs in mid-summer, which causes damage to upland crops and reduces yield and yield stability (Wang et al. 2002). Aerobic rice, which is adapted to aerobic non-flooding soils like wheat and maize but still tolerates flooding, is ideally suited for such dual flood-prone and drought-prone areas (Bouman et al. 2006; Yang et al. 2005). Therefore, the interest in 'aerobic rice'—'winter wheat' systems is increasing in the Huai River Basin (Bouman et al. 2007a; Feng et al. 2007).

Some recent research focused on water use and yield potential of aerobic rice (Bouman et al. 2005, 2006; Yang et al. 2005), but its response to fertilizers and nutrient-use efficiency have rarely been documented. The shift from flooded to aerobic soil conditions causes changes in soil water status, soil aeration and nutrient availability (Timsina and Connor 2001). Generally, rice plants are very sensitive to water stress when exceeding critical levels of soil water deficits; it was reported that leaf expansion in lowland rice stops completely with root-zone soil water pressure potential exceeding 50 kPa (Wopereis et al. 1996). Scientific findings on the physiological responses to various levels of water stress in aerobic rice are lacking. High water-use efficiencies (WUE) and water productivities (WP) have been reported for AR-systems (Bouman et al. 2005), when the yield penalty is relative small compared to the saving on water use. However, in studying crop responses to nutrients interactions with water availability may play a significant role. In flooded rice with saturated anaerobic soils, ammonium is the dominant form of available N. But, in aerobic rice systems, the dominant form of N is nitrate, which results in different pathways of N losses and N availability (Belder et al. 2005; Wade et al. 1998). Moreover, it has been suggested that, unlike lowland rice cultivars that have a preference for ammonium-N uptake, aerobic rice cultivars have a preference for nitrate-N uptake (Lin et al. 2005). Belder et al. (2005) compared fertilizer-N uptake and recovery in flooded and aerobic rice systems, and reported that aerobic rice was more limited by N than flooded rice.

Lowland rice-wheat cropping systems are practiced in many regions of Asia, but often operate at a low yield level because of inadequate nutrient and water management (Timsina and Connor 2001). Although many studies have investigated the productivity of lowland rice-wheat cropping systems (Alam et al. 2006; Yadav 2003; Yadvinder-Singh et al. 2000), no studies have looked into the productivity and nutrient use of 'aerobic rice'—'winter wheat' systems. The objective of our study was to evaluate quantitatively the yield response to macronutrients (N, P, and K), and the effects of nutrient omissions on yield formation and on the associated nutrient-use efficiencies for a new, water-saving crop rotation of 'aerobic rice' and 'winter wheat in the northern China plain. The study was carried out for only two alternating cropping sequences. Longer term experiments would give the findings a stronger underpinning; however, we could not collect data for a prolonged period since the site was closed. The study mainly serves to identify white spots in the nutrient dynamics of a new cropping system as a trigger for further research.

Materials and methods

Site characteristics

We conducted field experiments in Shuanghu village (33°17′N, 116°33′E, 27 m altitude), located in the Huai River Basin, Mengcheng County, Anhui Province, China. The site has a temperate, subhumid monsoon climate. The mean annual temperature is 14.8°C and the mean annual precipitation is 824 mm. The soil is classified as Fluvisol derived from river sediments. Ten soil samples were collected randomly from 0 to 30 cm soil depth throughout the field before the initiation of the experiment and analyzed for soil physical and chemical properties. Soil samples were air-dried at room temperature for 2 weeks, and passed through a 2-mm sieve prior to laboratory analysis. Sand, silt, and clay contents were determined by particle-size analysis using the hydrometer method (Gee and Bauder 1986). Soil pH (1:2.5 soil:water ratio), total organic C (the Walkley and Black method), total nitrogen (the Kjeldahl method), total P (the colorimetric method), total K (atomic absorption spectrometry), extractable P (the Olsen's method), and available K (with ammonium acetate) were determined following procedures described in Page et al. (1982). Main physical and chemical soil properties are presented in Table 1.

Table 1 Physical and chemical soil properties of the surface (0–30 cm) profile at the experimental site measured in 2005

Soil parameter	Value
Sand 0.05–2 mm (%)	10
Silt 0.002–0.05 mm (%)	58
Clay <0.002 mm (%)	32
pH (2.5:1)	7.5
Organic C (g kg^{-1})	8.7
Total N (g kg^{-1})	1.4
Total P (g kg^{-1})	0.4
Total K (g kg^{-1})	22.7
Mineral N (mg kg^{-1})	21
Olsen-P (mg kg^{-1})	12.6
Available K (mg kg^{-1})	106.9

Layout of experiments

The field experiments were conducted as aerobic rice—winter wheat rotation systems in 2005 and 2006. Five fertilizer treatments were set up in each experiment. The layout was a randomized complete block-design with four replications. The plot area was 5×4 m = 20 m^2. The cropping sequences were 'aerobic rice'—'winter wheat' (AR-WW) from June 2005 to June 2006 and 'winter wheat'—'aerobic rice' (WW-AR) from October 2005 to October 2006. In the AR-WW system, aerobic rice was grown in summer 2005 and winter wheat from autumn to spring in 2005–2006. In the WW-AR system, winter wheat was grown from autumn to spring in 2005–2006 (similarly as winter wheat in the AR-WW system) and aerobic rice in the summer of 2006. Before the start of the AR-WW rotation in summer 2005, the field was cropped to winter wheat and before the start of the WW-AR rotation in autumn 2005, the field was cropped to aerobic rice. Both preceding crops were uniformly cultivated.

The fertilizer treatments consisted of a complete dose of N, P, and K (NPK), doses with omissions of N (PK), P (NK) or K (NP), and a control without adding any macro-element (CK). In the AR-WW as well as the WW-AR system, the fertilizer treatments were kept the same for both crops; however, the dose of the component nutrients was adapted to the requirements of winter wheat and aerobic rice (Table 2). Fertilizer rates for aerobic rice and winter wheat were based on the significant differences in growth duration and soil nutrient mineralization status due to the obvious differences in weather condition between the two crop seasons. It was assumed that crop growth in the NPK treatment was not limited by macro-nutrients.

Table 2 Fertilizer nutrient rates (kg ha^{-1}) applied to aerobic rice and winter wheat crops

Treatment	Aerobic rice			Winter wheat		
	N	P	K	N	P	K
NPK	120	21.8	62.2	180	21.8	74.7
PK	0	21.8	62.2	0	21.8	74.7
NK	120	0	62.2	180	0	74.7
NP	120	21.8	0	180	21.8	0
Control	0	0	0	0	0	0

The fertilizers used were urea (46% N), single superphosphate (12% P_2O_5), and potassium chloride (60% K_2O). Phosphate was applied before sowing and incorporated during land preparation. Aerobic rice received 40% of the total N as a basal dressing, whereas the remainder was top-dressed in two splits (20% at tillering and 40% at stem elongation). K was applied with 50% as a basal dose and 50% top-dressed at stem elongation. Winter wheat received 40% of the total N as a basal dressing before sowing, whereas the remainder was top-dressed in two splits (40% at stem elongation and 20% at booting). Some 50% of the K was applied before sowing and 50% top-dressed at stem elongation.

Aerobic rice cv. Han Dao 502 was drilled on June 10 (both years) in rows spaced 30 cm apart at a seeding rate of 45 kg ha^{-1} in 2005 and 75 kg ha^{-1} in 2006. Following farmers' practices, supplementary surface irrigation of 60 mm was applied on June 16, June 22, and August 3 in 2005, and on June 11, June 17, August 8, and August 22 in 2006. The rice crops were harvested on October 19 in 2005 and on October 10 in 2006. All plots were kept free of weeds by an application of pre-emergence herbicide and hand-weeding after crop establishment. Pesticides were applied as appropriate for good practices in crop protection.

In both AR-WW and WW-AR, winter wheat cv. Yumai 18 was sown on October 23, 2005, in rows spaced 20 cm apart at a seeding rate of 188 kg ha^{-1}. The crop was harvested on June 1, 2006. Surface irrigations of 60 mm were applied on March 11 and April 9 after broadcasting of the fertilizers. Plots were hand-weeded after crop establishment.

Sampling and measurements

Temperature and sunshine data were collected from a weather station, and rainfall from two rainfall gauges, adjacent to the experimental field. During the aerobic rice season, soil moisture tension was measured daily in 2005 and every 2 days in 2006 using tensiometers installed at 15–20 cm depth. Groundwater depth was measured weekly using perforated tubes of 2 m depth.

At physiological maturity of aerobic rice and winter wheat, samples of 50 culms per plot were randomly selected and cut at ground level. Grain and straw were separated, oven-dried to constant weight at 70°C, weighed, and finely ground for N, P, and K analyses following Kjeldahl digestion with H_2SO_4–H_2O_2 (Wolf 1982). N content was determined by semimicro–Kjeldahl digestion and distillation (Nelson and Sommers 1980). P content was determined by the vanadomolybdate yellow method (Jackson 1958). K content was measured using an atomic absorption spectrometry. All analyses were done in duplicate. The chemical composition of plant parts is presented as nutrient content (g kg^{-1}). Nutrient uptake (N, P, K) in grains and straw was computed by multiplying content by dry weight. The dry matter harvest index (DM-HI) was calculated as the ratio of weight of grains and weight of grains plus straw. The nutrient harvest index was calculated as the ratio of nutrient uptake in grains and nutrient uptake in grains and straw (N-HI for N, P-HI for P, and K-HI for K) multiplied by 100. At harvest, aboveground biomass and grain yield were determined from a 12 m^2 area in the center of each plot. Grain yield was corrected to 14% moisture content.

Data analysis

The yield differences among fertilizer treatments were used to determine the yield losses caused by N, P, or K omission. The supply of indigenous soil nutrients was derived from the control treatment and the omission plots without a specific nutrient application. The apparent nutrient recoveries were calculated as:

1. Apparent N Recovery (AR-N) = $(U_{NPK} - U_{PK})/N_a$

2. Apparent P Recovery (AR-P) = $(U_{NPK} - U_{NK})/P_a$
3. Apparent K Recovery (AR-K) = $(U_{NPK} - U_{NP})/K_a$

where U_{NPK}, U_{PK}, U_{NK}, and U_{NP} are the nutrient uptake in the aboveground biomass (in the suffixed treatment plot), and N_a, P_a, and K_a are the fertilizer nutrient application rates in these treatment plots. The physiological nutrient-use efficiencies were derived from the relationship between grain yield and aboveground total nutrient uptake (PE-N for N, PE-P for P, and PE-K for K).

Analysis of variance was performed using SAS (SAS Institue 1999) to test the statistical significance of effects of fertilizer treatment for each crop. Statistical significances between mean differences among treatments for various parameters (aboveground biomass, grain yield, yield components, crop N, P, and K content and uptake, harvest indices of biomass, N, P, and K) were analyzed using the least significant difference (LSD) at the 0.05 probability level. Pair-wise comparisons of wheat or rice as a first crop and a second crop with the same fertilizer treatment were carried out for aboveground biomass, yield, yield components, N, P, and K content and uptake of each crop and for aboveground biomass and yield of the whole cropping sequence. Pearson correlation coefficients were calculated to assess the relationships among grain yield and yield components.

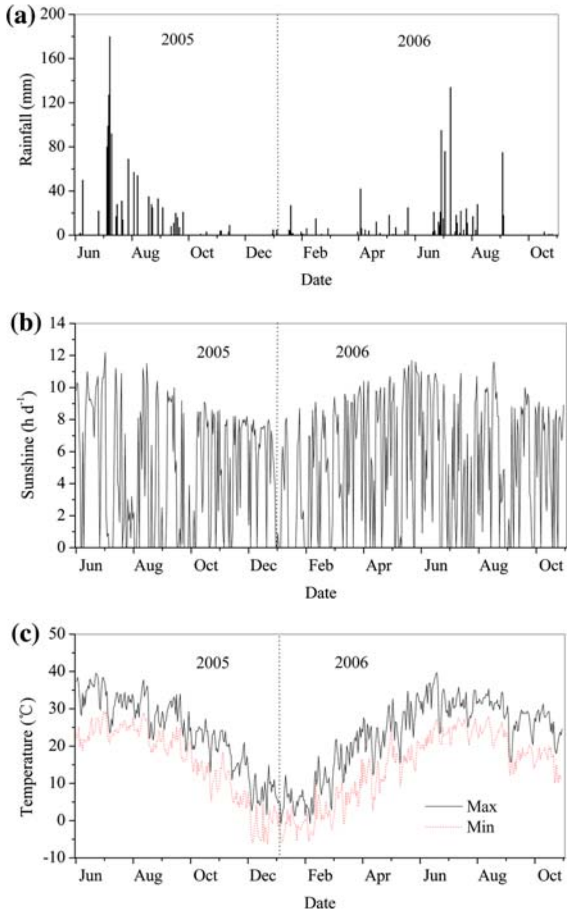

Fig. 1 Seasonal dynamics in **a** Rainfall (mm days^{-1}), **b** Sunshine (h days^{-1}), and **c** Ambient temperature (°C) at the experimental site in 2005 and 2006

Results

Weather, groundwater depth, and soil moisture tension

The mean air temperature in the aerobic rice season, from June to October, was 25.1°C in 2005 and 25.2°C in 2006. The number of average daily sunshine hours was 4.7 in 2005 and 5.3 in 2006. The total rainfall in the aerobic rice season was 1,098 mm in 2005 and 629 mm in 2006 (Fig. 1). In 2005, rainfall was much higher than the multi-annual average; especially, in July and August. The rainfall in July 2005 was 67% of the seasonal total, whereas, in July 2006, it was 51% of the seasonal total. Groundwater depth in the aerobic rice season fluctuated 90 cm below the soil surface in 2005 (Fig. 2). In 2006, it centered on 50–60 cm from early July to mid-August, and reached about 180 cm during grain filling towards the end of the season. The soil moisture tension during the aerobic rice season was much lower in 2005 than in 2006 (Fig. 3), indicating the risk on drought stress. In 2005, the moisture tension stayed mostly below 10 kPa, with an average of 4 kPa for the whole growth period. In 2006, the soil moisture tension reached values as high as 95 kPa in late September, with a seasonal average value of 30 kPa.

Aboveground biomass and grain yield

Nutrient availability, determined by fertilizer treatments and indigenous soil nutrient supply, significantly affected the aboveground biomass accumulation and

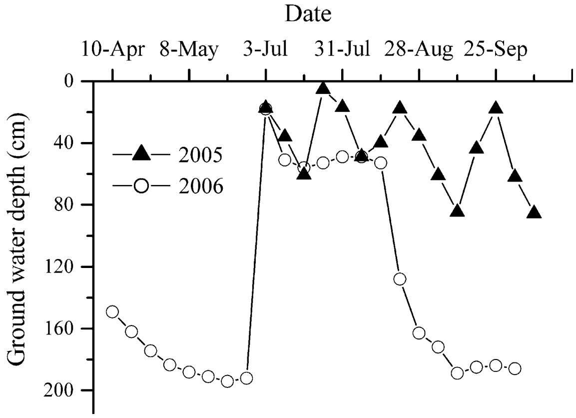

Fig. 2 Groundwater depth at the experimental site during the study period in 2005 and 2006

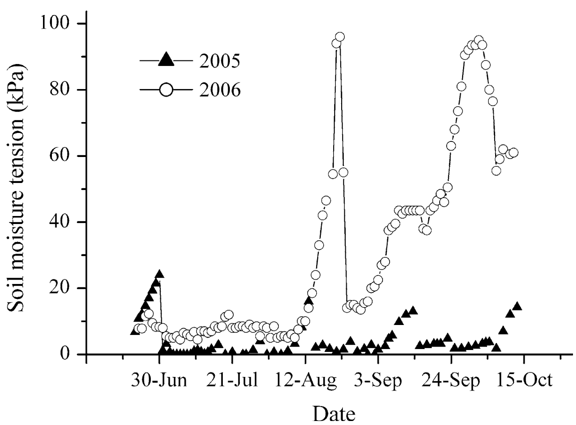

Fig. 3 Soil moisture tension (k Pa) at 15–20 cm depth during the aerobic rice crop from June to October in 2005 and 2006

grain yields of aerobic rice and winter wheat (Table 3). The aboveground biomass of aerobic rice ranged from 7.0 to 9.7 t ha^{-1} for AR-WW in 2005 and from 6.3 to 9.0 t ha^{-1} for WW-AR in 2006, and of winter wheat from 5.4 to 13.6 t ha^{-1} in AR-WW and from 10.0 to 14.9 t ha^{-1} in WW-AR. Grain yields of aerobic rice varied from 3.2 to 4.1 t ha^{-1} in AR-WW and from 2.9 to 4.0 t ha^{-1} in WW-AR, whereas yields of winter wheat varied from 2.7 to 7.1 t ha^{-1} in AR-WW and from 4.4 to 6.6 t ha^{-1} in WW-AR.

For both aerobic rice and winter wheat, the aboveground biomass and grain yields were strongly associated with N fertilizer rate. The reduction in aboveground biomass of aerobic rice caused by N omission was about 2.5 t ha^{-1} in both cropping sequences. For winter wheat, these reductions were much larger: 6.9 t ha^{-1} in AR-WW and 3.2 t ha^{-1} in WW-AR. The yield loss caused by the omission of N was for winter wheat, 4.3 t ha^{-1} in AR-WW and 1.6 t ha^{-1} in WW-AR, and for aerobic rice, 0.5 t ha^{-1} in AR-WW and 0.8 t ha^{-1} in WW-AR. Thus, cumulative omission of N reduced aboveground biomass and grain yield of winter wheat more than of aerobic rice. In a pair-wise comparison of the two cropping sequences it turned out that the N-omission plot and the control showed a significantly higher biomass and grain yield of wheat in the WW-AR in comparison to the AR-WW system, whereas, for aerobic rice only the yield of the control was significantly different: about 0.4 t ha^{-1} lower in WW-AR compared to AR-WW. Thus, yield stability of aerobic rice is much less affected than winter wheat by the effects of the rotation on N-availability.

Grain yields of aerobic rice were not significantly different among NPK, NK, and NP treatments in both cropping sequences (Table 3). The yield reductions in winter wheat were 1.6 t ha^{-1} with omission of P and 1.2 t ha^{-1} with omission of K in AR-WW. On an annual basis, the combined yield of ‘aerobic rice’ and ‘winter wheat’ decreased by 46% with omission of N, 13% with omission of P, and 7% with omission of K in AR-WW, and by 23% with N omission, 6% with P omission, and 1% with K omission in WW-AR.

Table 3 Effects of nutrient omissions on aboveground biomass and grain yield (t ha^{-1}) of aerobic rice and winter wheat in the AR-WW and WW-AR cropping sequences

Treatment	Aerobic rice		Winter wheat		Combined crops	
	Biomass	Yield	Biomass	Yield	Biomass	Yield
AR-WW						
NPK	9.7 a	3.7 a	13.6 a	7.1 a	23.4 a	10.9 a
PK	7.3 b	3.2 b	6.7 c	2.8 c	14.0 b	5.9 b
NK	9.6 a	4.1 a	11.5 b	5.5 b	21.1 a	9.5 a
NP	9.6 a	4.1 a	12.7 ab	5.9 b	22.4 a	10.1 a
CK	7.0 b	3.3 b	5.4 c	2.7 c	12.4 b	6.0 b
WW-AR						
NPK	9.0 a	3.8 a	14.9 a	6.6 a	23.9 a	10.4 a
PK	6.5 b	3.0 b	11.7 bc	5.0 b	18.2 bc	8.0 b
NK	8.1 a	3.7 a	13.1 ab	6.1 a	21.2 ab	9.8 a
NP	8.8 a	4.0 a	13.7 ab	6.4 a	22.5 a	10.4 a
CK	6.3 b	2.9 b	10.0 c	4.4 b	16.3 c	7.3 b

For each cropping sequence, different letters within a column indicate significant differences at $P < 0.05$

Yield components

In aerobic rice, N omission reduced the number of panicles and the number of spikelets (Table 4). The omission of P and K had no significant effect on any of the yield components. The percentage of filled spikelets and 1,000-grain weight were hardly affected by omission of any of the elements. Grain yield of aerobic rice was mainly determined by the number of panicles per square meter and the number of spikelets per panicle, and slightly correlated with 1,000-grain weight (Table 5). Thus, in aerobic rice nutrient availability affected sink formation more than source capacity. The number of spikelets per panicle was negatively correlated with the percentage of filled spikelets. In the pair-wise comparison of the two systems for aerobic rice it turned out that the spikelets per panicle and the number of filled spikelets was generally significantly different in AR-WW compared to WW-AR. This could have been affected by moisture stress (Figs. 2, 3).

In winter wheat, the number of spikes per square meter was significantly lower in the N omission and control plots than in the NPK plot, in both AR-WW and WW-AR (Table 4). With the omission of P, the number of spikes decreased only in AR-WW. The omission of K had no significant effect on the number of spikes. The number of grains per spike decreased with the omission of N, especially in AR-WW, but was not affected by omission of P and K. The omission of N and P increased 1,000-grain weight significantly. Grain yield was positively correlated with the number of spikes per square meter and the number of grains per spike, and negatively correlated with 1,000-grain weight (Table 5). Thus, in winter wheat nutrient availability affected sink formation as well as source capacity.

Nutrient content and uptake

Mostly the nutrient contents, expressed as mass fraction (g kg^{-1}), were lower in the second crop of the rotation for aerobic rice as well as for winter wheat (Table 6), as a consequence of soil nutrient depletion by the preceding crop. In aerobic rice, the N contents of grain and straw were significantly lower in N omission plots than in NPK plots, for both cropping sequences (Table 6). The P content decreased by P omission, especially, in WW-AR. The K content was hardly affected in rice grown as first crop of the rotation (AR-WW); however, K omission affected K content of the straw in the succeeding crop (WW-AR).

The N content of grain and straw of winter wheat was significantly lower in the N omission plots than in the NPK plots (Table 6). N content of the grain

Table 4 Effects of nutrient omissions on yield components of aerobic rice and winter wheat in the AR-WW and WW-AR cropping sequences

Treatment	Aerobic rice				Winter wheat		
	Number of panicles (m^{-2})	Spikelets per panicle ($panicle^{-1}$)	Filled spikelets (%)	1,000-grain weight (g)	Number of spikes (m^{-2})	Grains per spike ($spike^{-1}$)	1,000-grain weight (g)
AR-WW							
NPK	216 a	114 a	51 a	31.7 b	446 a	31 a	43.9 b
PK	170 b	103 b	50 ab	31.9 ab	251 c	22 b	49.2 a
NK	229 a	109 ab	50 ab	31.9 ab	337 b	32 a	48.2 a
NP	222 a	113 a	48 ab	31.8 ab	419 a	32 a	39.9 c
CK	165 b	102 b	44 b	32.5 a	247 c	18 c	48.9 a
WW-AR							
NPK	195 ab	98 a	63 c	31.5 a	459 a	29 a	42.5 b
PK	189 b	77 b	69 b	30.6 a	370 b	25 b	48.1 a
NK	210 a	84 ab	65 c	32.1 a	390 ab	30 a	46.6 a
NP	202 ab	97 a	66 bc	31.1 a	432 ab	31 a	41.5 b
CK	189 b	69 b	75 a	31.3 a	285 c	29 a	48.5 a

For each cropping sequence, different letters within a column indicate significant differences at $P < 0.05$

Table 5 Correlation coefficients (*R*) of the association among variables (grain yield and yield components) for all treatments of aerobic rice and winter wheat crops ($N = 40$)

Variable	Aerobic rice				
	Grain yield	Panicles	Spikelets per panicle	Filled spikelets	1,000-grain weight
Grain yield (t ha^{-1})	1.00	0.66**	0.66**	−0.30	0.32*
Panicles (nr m^{-2})		1.00	0.22	−0.03	0.02
Spikelets per panicle (nr m^{-2})			1.00	−0.74**	0.46**
Filled spikelets (%)				1.00	−0.38*
1,000-grain weight (g)					1.00

	Winter wheat			
	Grain yield	Spikes	Grains per spike	1,000-grain weight
Grain yield (t ha^{-1})	1.00	0.89**	0.74**	−0.66**
Spikes (nr m^{-2})		1.00	0.64**	−0.70**
Grains per spike (nr $spike^{-1}$)			1.00	−0.49**
1,000-grain weight (g)				1.00

* Significant at $P < 0.05$, ** Significant at $P < 0.01$

Table 6 Effects of nutrient omissions on nitrogen (N), phosphorus (P), and potassium (K) content (g kg^{-1}) in grain and straw of aerobic rice and winter wheat crops in the AR-WW and WW-AR cropping sequences

Treatment	Aerobic rice						Winter wheat					
	N		P		K		N		P		K	
	Grains	Straw	Grains	Straw	Grains	Straw	Grains	Straw	Grains	Straw	Grains	Straw
AR-WW												
NPK	13.3 a	10.0 a	2.9 ab	1.2 a	4.0 a	14.9 a	21.7 a	5.7 b	3.1 c	0.7 a	4.4 a	11.6 a
PK	11.5 ab	7.5 b	3.2 ab	1.5 a	4.0 a	16.1 a	13.6 b	3.4 c	3.6 b	0.7 a	4.5 a	9.9 c
NK	13.4 a	9.5 a	2.8 b	1.0 a	3.8 a	16.4 a	21.7 a	6.5 ab	2.8 d	0.5 b	4.1 b	11.9 a
NP	13.2 a	9.9 a	3.1 ab	1.4 a	4.1 a	15.4 a	19.9 a	7.8 a	3.2 c	0.7 a	4.5 a	8.6 b
CK	10.9 b	7.8 b	3.3 a	1.2 a	3.8 a	15.6 a	13.8 b	3.6 c	3.8 a	0.6 ab	4.4 a	8.8 c
WW-AR												
NPK	12.1 ab	7.6 a	2.4 b	1.0 a	3.4 a	15.0 a	21.2 a	7.1 a	3.2 bc	0.8 a	4.4 ab	12.6 a
PK	10.2 c	4.7 b	2.9 a	1.0 a	3.5 a	13.4 ab	15.3 b	3.9 b	3.4 ab	0.5 a	4.4 ab	10.2 b
NK	11.8 ab	7.7 a	2.1 c	0.8 b	3.1 b	14.5 a	21.5 a	6.6 a	3.1 c	0.5 a	4.3 b	12.1 a
NP	12.7 a	7.7 a	2.4 b	1.1 a	3.3 ab	12.8 b	21.3 a	6.7 a	3.3 abc	0.7 a	4.5 a	10.3 b
CK	10.7 bc	4.9 b	2.8 a	1.0 a	3.4 a	12.5 b	16.9 b	3.8 b	3.4 a	0.5 a	4.5 ab	10.0 b

For each cropping sequence, different letters within a column indicate significant differences at $P < 0.05$

decreased by 28% in WW-AR and by 37% in AR-WW by N omission. P content was lowest in the P omission treatments. The omission of N or K reduced the K content of the straw. Variations in grain nutrient contents are shown as the relationship between grain nutrient uptake and yield for N, P and K in rice (Fig. 4a–c) and in wheat (Fig. 4d–f). The effects of nutrient treatments on the N, P and K-contents are largest for N. However, the variations in those values are within boundaries that are normal for both crops.

The total uptake of nutrients by aerobic rice and winter wheat was significantly affected by fertilizer treatments (Table 7). In aerobic rice, the omission of N significantly reduced N and K uptake, in both cropping sequences. N uptake by grains decreased by

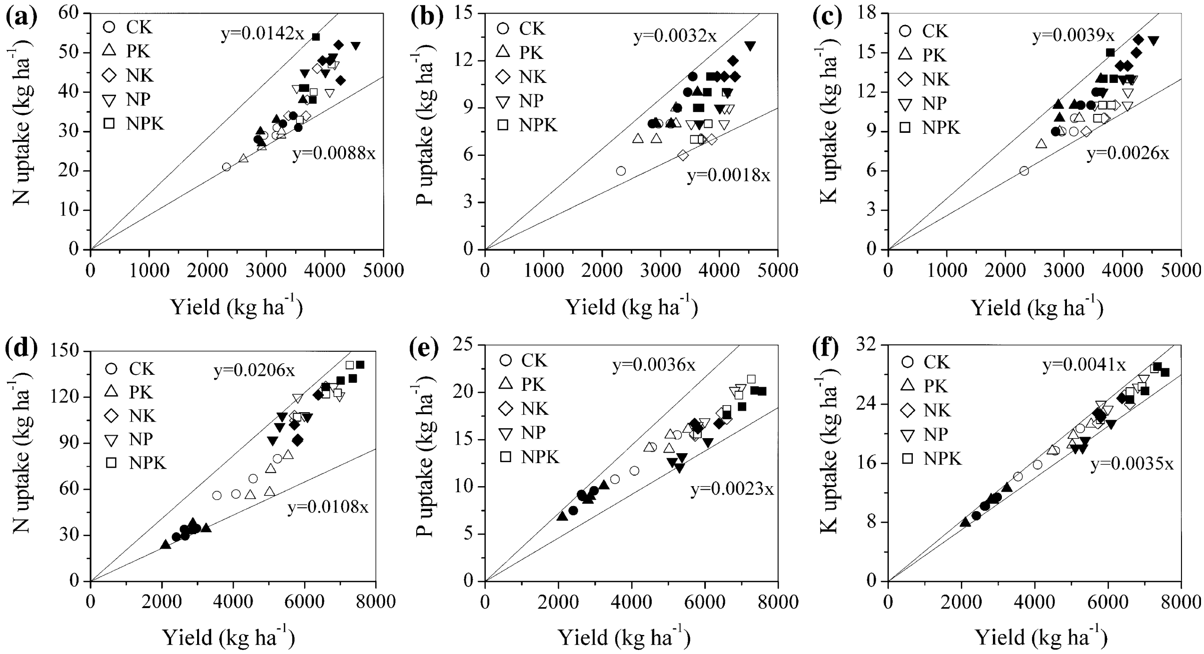

Fig. 4 Yield versus nutrient uptake in grains for aerobic rice for N (**a**), P (**b**), and K (**c**), and for winter wheat for N (**d**), P (**e**), and K (**f**). *Filled symbols* are the AR-WW sequence and *open symbols* are the WW-AR sequence

26% in AR-WW and by 33% in WW-AR, and N uptake by the whole plant decreased by 38% in AR-WW and by 45% in WW-AR. K uptake by the whole plant decreased by 23% in AR-WW and by 36% in WW-AR. Like for aboveground biomass and grain yield, uptake of N, P, and K were hardly affected by P or K omission.

In winter wheat, the total uptake of N, P, and K was much lower in the N omission and control plots than in the NPK, P, and K omission plots. Compared with the NPK plots, nutrient uptake by grain in N omission plots decreased in WW-AR by 45% for N, 20% for P, and 25% for K. In AR-WW, the uptake decreased by 76% for N, 55% for P, and 60% for K. The grain N uptake was also significantly reduced by omission of P or K in AR-WW.

N uptake by aerobic rice in control plots amounted to 60 kg ha^{-1} in AR-WW and 44 kg ha^{-1} in WW-AR, whereas, in winter wheat, the uptake was 86 kg ha^{-1} in WW-AR and 42 kg ha^{-1} in AR-WW. Thus, soil nutrient depletion by the preceding crop decreased N uptake of the succeeding crop. In the pair-wise comparison the differences in N uptake in wheat were only significant for the N-omission and control plots. The total N uptake derived from indigenous soil N combined for both crops, aerobic rice and winter wheat, in a double cropping system amounted to 102 kg ha^{-1} in AR-WW and 130 kg ha^{-1} in WW-AR. Thus, winter wheat as first crop in the rotation benefitted more of soil N reserves than aerobic rice.

Harvest index

Nutrient availability significantly affected harvest-indices for dry matter (DM-HI), nitrogen (N-HI), phosphorus (P-HI) and potassium (K-HI) (Table 8). Compared with the full NPK treatment, N omissions generally influenced all indices, though the control was hardly affected. N, P, or K omission significantly increased the DM-HI of aerobic rice in AR-WW but not in WW-AR. The N harvest-index (N-HI) of aerobic rice significantly increased by omission of N, in both cropping sequences indicating a more efficient N relocation from the vegetative parts to the seeds. The N-HI of aerobic rice was consistently higher in WW-AR than in AR-WW, reflecting a lower N uptake in the biomass, but a more efficient N relocation to the grain in WW-AR. The P and K harvest indices of aerobic rice were also higher in WW-AR than in AR-WW, and slightly increased with omission of N. The omission of P and K had

Table 7 Effects of nutrient omissions on nitrogen (N), phosphorus (P), and potassium (K) uptake (kg ha^{-1}) by aerobic rice and winter wheat crops in the AR-WW and WW-AR cropping sequences

Treatment	Aerobic rice									Winter wheat								
	N			P			K			N			P			K		
	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total	Grain	Straw	Total
AR-WW																		
NPK	43 a	57 a	100 a	10 ab	7 a	16 ab	13 a	85 a	99 a	135 a	38 a	173 a	19 a	4 a	24 a	27 a	76 a	104 a
PK	32 b	30 b	62 b	9 b	6 ab	15 b	11 b	64 bc	76 bc	33 c	13 b	45 c	9 d	2 bc	11 c	11 d	37 c	48 c
NK	48 a	51 a	99 a	10 ab	6 ab	16 ab	14 a	89 a	102 a	104 b	39 a	143 b	13 c	3 b	16 b	20 c	71 a	91 ab
NP	48 a	52 a	100 a	11 a	8 a	19 a	15 a	81 ab	96 ab	104 b	52 a	156 ab	17 b	5 a	22 a	24 b	57 b	80 b
CK	31 b	28 b	60 b	9 ab	4 b	14 b	11 b	57 c	68 c	32 c	10 b	42 c	9 d	2 c	11 c	10 d	24 d	34 d
WW-AR																		
NPK	40 a	38 a	78 a	8 ab	5 a	13 ab	11 a	75 a	86 a	124 a	57 a	181 a	19 a	6 a	25 a	26 a	102 a	128 a
PK	27 b	16 b	43 b	8 ab	4 b	11 abc	9 b	45 bc	55 bc	68 b	26 b	93 b	15 bc	3 bc	18 c	19 b	67 bc	86 bc
NK	38 a	33 a	71 a	7 b	3 b	10 c	10 ab	64 a	74 a	116 a	46 a	161 a	17 ab	4 bc	20 bc	23 a	84 ab	107 ab
NP	44 a	37 a	81 a	8 a	5 a	14 a	12 a	61 ab	72 ab	119 a	48 a	167 a	19 a	5 ab	24 ab	25 a	75 bc	100 b
CK	27 b	16 b	44 b	7 ab	4 b	11 bc	9 b	42 c	51 c	65 b	21 b	86 b	13 c	3 c	16 d	17 b	56 c	73 c

For each cropping sequence, different letters within a column indicate significant differences at $P < 0.05$

Table 8 Effects of nutrient omissions on harvest-index of dry matter (DM-HI), N (N-HI), P (P-HI), and K (K-HI) (%) of aerobic rice and winter wheat in the AR-WW and WW-AR cropping sequences

Treatment	Aerobic rice				Winter wheat			
	DM-HI	N-HI	P-HI	K-HI	DM-HI	N-HI	P-HI	K-HI
AR-WW								
NPK	34 c	43 b	60 b	14 b	46 a	79 a	82 ab	27 b
PK	38 b	51 a	59 b	15 ab	36 b	72 ab	78 b	23 c
NK	37 b	49 a	64 ab	13 b	42 a	73 ab	82 ab	22 c
NP	38 b	48 ab	60 b	15 ab	41 a	67 b	77 b	29 ab
CK	41 a	53 a	70 a	16 a	44 ab	77 a	85 a	31 a
WW-AR								
NPK	37 a	51 b	62 c	13 c	39 a	68 b	75 b	20 c
PK	41 a	63 a	68 a	17 ab	38 a	73 ab	81 ab	23 abc
NK	40 a	54 b	67 ab	14 bc	41 a	72 ab	82 a	22 bc
NP	39 a	55 b	63 bc	16 abc	41 a	71 ab	79 ab	25 a
CK	41 a	63 a	68 a	17 a	39 a	76 a	82 a	24 ab

For each cropping sequence, different letters within a column indicate significant differences at $P < 0.05$

little effect on the N-HI, P-HI, and K-HI of aerobic rice. In winter wheat, N and P omission had no effect on N-HI and P-HI. Although the omission of K generally had no effect on N-HI and P-HI, it increased K-HI significantly.

Nutrient-use efficiency

Apparent nutrient recoveries (ANR) were higher in winter wheat than in aerobic rice. In aerobic rice, the ANR values for N, P and K amounted to 0.32, 0.01, and 0.03 in the AR-WW system, while in the WW-AR system those values were 0.30, 0.06, and 0.19, respectively. In winter wheat, the ANR values for N, P and K were 0.71, 0.15, and 0.26 in the AR-WW system, while in the WW-AR system those were 0.49, 0.09, and 0.31, respectively.

The physiological nutrient-use efficiencies (PE) were derived from the relationship between grain yield and total nutrient uptake in the aboveground biomass (Fig. 5). In aerobic rice, the physiological efficiency of N (N-PE) ranged from 32 to 74 kg kg^{-1}, that of P from 198 to 378 kg kg^{-1}, and that of K from 32 to 66 kg kg^{-1} (Fig. 5a, b, c). The efficiencies were higher in the WW-AR than in the AR-WW rotation.

In winter wheat, N-PE ranged from 35 to 71, P-PE from 212 to 362, and K-PE from 49 to 96 kg kg^{-1}. The physiological nutrient-use efficiencies were slightly higher in AR-WW than in WW-AR, especially in the control and N omission treatments (Fig. 5d, e, f), indicating that a low nutrient supply increased physiological efficiencies.

Discussion

Compared with the full application of all macro-elements, the omission of N significantly decreased the aboveground biomass and grain yields of aerobic rice and winter wheat, whereas the omission of P and K had relatively little effect. In aerobic rice, panicle density and the number of spikelets per panicle decreased with N omission. In both rice and wheat, relative yield reductions increased with consecutive omissions of N, highlighting the importance of N for crop growth and grain yield formation, especially in winter wheat. These results correspond to similar findings by Balasubramanian et al. (2003), who studied irrigated lowland rice–wheat systems in South Asia. The larger yield reductions in winter wheat than in aerobic rice caused by N omission treatments, are a consequence of the higher N demand of winter wheat compared to aerobic rice (Cui et al. 2008; Belder et al. 2005).

The relatively small response in aerobic rice yield to an omission of P or K in AR-WW may indicate an adequate soil P and K supply for aerobic rice.

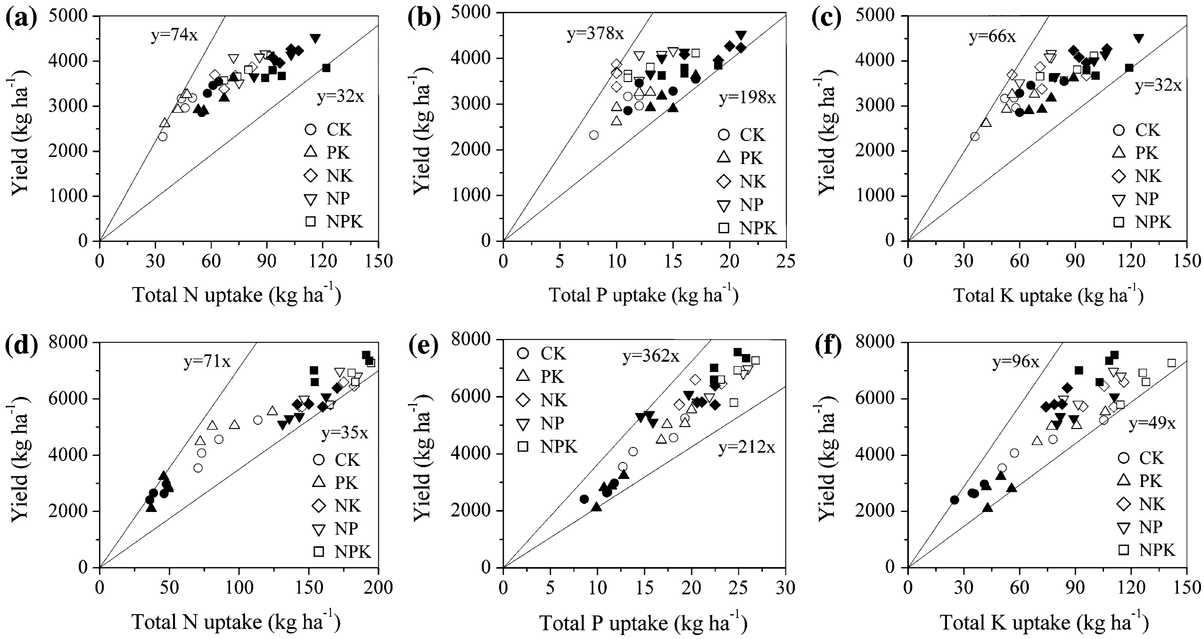

Fig. 5 Yield versus nutrient uptake in the aboveground biomass for aerobic rice for N (**a**), P (**b**), and K (**c**), and for winter wheat for N (**d**), P (**e**), and K (**f**). *Filled symbols* are the AR-WW sequence and *open symbols* are the WW-AR sequence

However, the apparent recovery of P in aerobic rice was extremely low indicating its poor P-capturing ability. In winter wheat, P and K were yield limiting in the WW-AR as well as the AR-WW rotation, suggesting a higher demand for these nutrients by wheat than by aerobic rice. Dobermann et al. (2003) reported that P and K are less limiting than N in irrigated lowland rice systems in South and Southeast Asia. Zhang and Wang (2005) reported that N was the most limiting nutrient in irrigated (lowland) rice systems, whereas P and K became limiting with continued cropping from the second to the fourth year. Wang et al. (2001) also reported that soil P and K supplies decreased to an amount at which crop growth and yields of lowland rice became reduced after 3–4 seasons for P and after 1–2 seasons for K.

The omission of N, P, or K had less effect on aerobic rice than on winter wheat, suggesting that the growth and yield of aerobic rice were more limited by other factors. In the growing season of 2005 low levels of incident photosynthetic radiation (IPAR) may have played a role, while in 2006 drought stress might have occurred although no visible signs on leaf morphology were noticed. It has been reported that the aerobic rice cultivar Han Dao 502 yields up to 5.5 t ha^{-1} with a corresponding aboveground biomass of 12 t ha^{-1} in an environment (Beijing region) with a longer crop growth duration of 149 days (Bouman et al. 2006). In the present study, the maximum yield of 4.1 t ha^{-1}, with an aboveground biomass of 9.6 t ha^{-1} (in AR-WW rotation) was lower, which may have been caused by growth duration reduction of some 28 days. Feng et al. (2007) also reported aerobic rice yields of 2.4–3.6 t ha^{-1} in experiments in 2003–04 in Panlou Village near Kaifeng in the Yellow River Basin (34°78′N, 114°52′E; 68 m altitude), which is close to our study site. However, they used the cultivar Han Dao 297, with about 10–15 days shorter growth duration than Han Dao 502. Compared with typical lowland rice grain yield (8.6–9.6 t ha^{-1}) in Fengtai, where is some 60 km away from our study site (Li et al. 2007), aerobic rice yields of this investigation were considerably lower. The lowland rice had some 25–30 days longer growth duration than the aerobic rice due to a seedling nursery period. Assuming a growth duration of 100 days, the average crop growth rate (CGR) ranged from 70 to 97 kg ha^{-1} days^{-1} in 2005 and from 63 to 90 kg ha^{-1} days^{-1} in 2006 for aerobic rice of this research. Under optimal conditions, the CGR should have been about 150 kg ha^{-1} days^{-1}. If these constraints were to be relieved, then the indigenous availability of N, P and K may become limiting as well, just as in the winter wheat crops. Winter wheat produced more aboveground biomass and grains with a higher N-content than aerobic rice, which resulted in a higher demand for nutrients; especially for N.

Plant N and P contents in grain and straw of aerobic rice and winter wheat were lowest in the respective N and P omission treatments, suggesting soil deficiencies of these nutrients. Since total nutrient uptake is a function of plant biomass production (Sheehy et al. 1998), the uptake of N, P, and K was not consistent with the content of these nutrients in these omission treatments. When N was deficient, N content in grain and straw decreased strongly, especially in winter wheat. This dilution of N in the vegetative parts reduced biomass production, an effect that has been reported by many researchers (e.g., Cabrera-Bosquet et al. 2007; Peng et al. 1995). In the pair-wise comparison of the two systems it turned out that the biggest effects of the cropping sequence on grain N uptake were found for wheat in the N-omission plots. Aerobic rice showed less sensitivity, which is in contrast with results reported by Belder et al. (2005). The poor yield and N response of aerobic rice grown in 2005 to N availability, also reflected in high N contents in the straw, might be caused by sink limitations. Low radiation levels resulting in less photosynthesis and thus a reduced carbohydrate availability do limit spikelet development (Liu et al. 2008). In 2006, some drought stress due to a high soil moisture tension (Fig. 3) may have affected the crop response to N.

The harvest-indices of N, P, and K of aerobic rice increased significantly with omission of N, especially in WW-AR. This suggests a more efficient relocation of the macro-nutrients from vegetative parts to grains under low availability of N. However, in winter wheat, the omission of N, P, and K reduced the harvest indices of N, P, and K in the second cycle (AR-WW), reflecting the severity of the nutrient deficiencies. The physiological efficiencies for N, P, and K of aerobic rice and winter wheat were higher in the second crop cycle (WW-AR for rice and AR-WW for wheat) than in the first, indicating that nutrient depletion by the preceding crops decreased the nutrient supply of the subsequent crops (especially in the omission plots). However, the increased efficiencies could not compensate for the nutrient shortages.

We found that plant N uptake derived from indigenous N supply (measured in N omission plots) and apparent N recovery are the most informative parameters for assessing the cumulative effects of N treatments on N availability. Fan et al. (2007) reported for their study in southwest China that good N management strategies in rice–wheat rotations decreased N losses and increased the yield of both rice and wheat. Various strategies exist to improve nutrient-use efficiencies, such as real-time N management reported by Peng et al. (2006). In our study, N deficiencies severely reduced yield and N content in grains.

Therefore, in developing sustainable cropping systems, nutrient supply and demand should be matched in time, and the total dosages should be related to the attainable (or targeted) yield of the cropping system (Spiertz and Schröder 2006). Janssen and De Willigen (2006) developed a framework for nutrient management that takes sustainable soil fertility, environmental protection, and balanced plant nutrition as starting points. Taking this framework into account, the Huai River Basin meets the conditions for optimum nutrient management. Agronomically, farmers should aim at a minimum input of each production resource required to allow maximum use of all other inputs (De Wit 1992). It was shown that N was the most limiting nutrient for growth and yield formation; especially for winter wheat in a cropping sequence with repeated N omissions. The responses to P and K omissions become most evident when N was not limiting. Aerobic rice was less sensitive to nutrient omissions, indicating that other factors (e.g., water) may have been limiting. Therefore, by developing fertilizer recommendations attainable yield under given agroecological conditions and the after effect of the cropping sequence on the nutrient release should be taken into account. However, these results need to be proven by a longer-term experiment. Shen et al. (2009) studying lucerne-wheat cropping systems, concluded that the overall variability in seasonal rainfall calls for adaptive management strategies. This may apply to tactical decisions like cultivar choice and nutrient management, but also to strategic choices as crop rotations, land reclamation or improving the biological, chemical and physical soil traits.

Conclusions

Aerobic rice was less sensitive to omission of N than winter wheat under the conditions on the 2005 and 2006 growing seasons; however, both crops responded stronger to N omission than P or K omission. N uptake from indigenous soil nutrient supply (N omission plots) and apparent N recoveries have shown to be reliable proxy parameters to assess the capability of aerobic rice–winter wheat systems to capture nutrients at low input levels of nutrients. The nutrient demand of aerobic rice was much lower than of winter wheat. The cumulative effect of N, P, and K omissions depended on the nutrient demand of succeeding crops in a cropping system. Improvements of crop productivity as well as nutrient-use efficiencies, should be brought about by developing cropping systems, by an appropriate choice of adapted cultivars, by a site- and time-specific fertilizer management and by eliminating other yield-limiting factors (e.g., micronutrients, drought) and yield-reducing factors (weeds, pests and diseases). It is recommended that analyses of nutrient requirements should not be based on the demands and attainable yield levels of sole crops only, but on the after-effects of nutrient availability on succeeding crops in a cropping system as well. A long-term, more detailed research effort is needed to quantify the crop responses to nutrients under different water regimes. Therefore, further research is needed to explore the sustainability of 'aerobic rice' based cropping systems with regard to nutrient-use efficiencies and water productivity in major crop rotations of the northern China plain.

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