Potassium Fertilization in Rice–Wheat System across Northern India: Crop Performance and Soil Nutrients

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ABSTRACT

Rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping in South Asia is under stress due to widespread removal of plant nutrients in excess of their application. We evaluated K, S, and Zn application to rice and wheat in 60 farmer's fields in five districts across northern India. We compared the existing farmer's fertilizer practice (FFP), which in most cases did not include application of K, S, or Zn, with application of K only, S + Zn, or K + S + Zn. Application of K increased rice yields by 0.6 to 1.2 Mg ha^{-1} and wheat yields by 0.2 to 0.7 Mg ha^{-1} across the locations varying in soil texture, soil K, climate, and irrigation. Application of S and Zn with K further increased yields. Added net return from fertilization with only K, as compared to FFP, ranged from U.S.$ 114 to 233 ha^{-1} for rice and U.S.$ 29 to 214 ha^{-1} for wheat. Added net return further increased when S and Zn were combined with K. Total plant K per unit of grain yield was comparable for mature rice and wheat (22 kg Mg grain^{-1}). Soil exchangeable and non-exchangeable K decreased without K application during one rice–wheat cropping cycle. Rice and wheat yields increased with application of K across the range in exchangeable soil K from 60 to 162 mg kg^{-1}. Approaches are needed to reliably predict fertilizer K requirements when crops respond relatively uniformly to K across a wide range in exchangeable K.

Rice–wheat rotation is one of the largest agricultural production systems of the world, occupying 13.5 million ha of cultivated land in the Indo-Gangetic Plains (IGP) in South Asia and several million hectares in China (Ladha et al., 2009). The intensively-cultivated rice–wheat system (RWS) is fundamental for employment, income generation, and livelihood security for millions in South Asia. It is practiced on many soil types and ecologies across the IGP. They include coarse- to fine-textured soils under arid to dry subhumid conditions of the Trans-Gangetic Plain (TGP) in Pakistan and northwestern India, coarse- to fine-textured loamy soils under semiarid to subhumid climate conditions of the Upper Gangetic Plain (UGP) in northern India, and sandy loam to clay soils under moist subhumid to dry subhumid climate conditions of the Middle Gangetic Plain (MGP) and the Lower Gangetic Plain (LGP) in northeastern India and Bangladesh.

In the TGP and UGP, both rice and wheat are grown under irrigated conditions, with a number of irrigations typically ranging from 15 to 30 for rice and 3 to 6 for wheat. The RWS in MGP and LGP is partially irrigated; rice receives fewer irrigations (5–10 irrigations) in the MGP than in the LGP (2–5 irrigations) (Sharma, 2003). Fertilizer use is highly variable across the IGP with mean application rates of N + P_2O_5 + K_2O for the RWS ranging from 258 kg ha^{-1} in the LGP to 444 kg ha^{-1} in the TGP (Sharma, 2003). The ratios of nutrients applied to crops typically do not match the ratios in which they are removed from the soils, and a decline in crop yields and factor productivity have been reported for the RWS, particularly in TGP and UGP (Singh et al., 2005).

Rice and wheat remove substantial quantities of nutrients from soil, which often exceed their replenishments through external sources leading to deterioration in soil fertility and emergence of multi-nutrient deficiencies (Ladha et al., 2003). Surveys in the IGP revealed that farmers often apply to the RWS greater than recommended rates of fertilizer N and P, but ignore the sufficient application of other nutrients (Singh et al., 2005). Potassium, S, and micronutrients are not applied in adequate amounts to prevent increasing deficiencies of these nutrients in RWS because farmers are often unaware of the benefits of these nutrients, and farmers are occasionally unable to obtain fertilizers with these nutrients during periods of peak demand. Insufficient credit might deter some farmers in the MGP and LGP.

The risk of nutrient mining can be particularly serious in areas with highly productive RWS and relatively lower levels of input of K, S, and micronutrients (Singh et al., 2008). Such unbalanced and inadequate use of nutrients can decrease the profitability of the RWS with increased environmental risks associated with loss of excess N from the root zone (Prasad, 2006). Application of N in excess of crop demand—limited by insufficient supply of K, S, or micronutrients—can result in leaching of nitrate into groundwater, especially for rice on

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Abbreviations: FFP, farmer's fertilizer practice; HI, harvest index; IGP, Indo-Gangetic Plains; LGP, Lower Gangetic Plain; MGP, Middle Gangetic Plain; RIE, reciprocal internal efficiency; RWS, rice–wheat system; SREY, rice equivalent yield for systems; TGP, Trans-Gangetic Plain; UGP, Upper Gangetic Plain.

coarse-textured soils in the TGP and UGP. Excess N can also enhance emission of nitrous oxide arising from nitrification–denitrification (Yadvinder-Singh and Bijay-Singh, 2001).

Cultivators' fields in the IGP are typically small with high spatial variability in management practices. Large variations in nutrient balances and nutrient requirements exist within a small distance due to differences in inherent soil fertility, crop residue management, historical fertilizer use, input of organic materials, fertilizer application method and schedule, and resources available to a farmer, which influence crop yields attainable with farmer's management practices. Blanket application of plant nutrients across large areas is typical in the IGP. This leads to inefficient use of added nutrients as application rates do not consider the spatial variability in nutrient requirements among the fields (Buresh et al., 2010). The tailoring of fertilizer requirements for field-specific needs of crops is necessary to improve productivity and profitability from fertilizer use. On-station studies revealed that site-specific nutrient management could enhance the annual productivity of the RWS as compared to the farmers' prevailing ad hoc nutrient management (Singh et al., 2008).

Farmers of the IGP often apply little or no K in the RWS, and there is increasing concern that soil K reserves are being depleted to levels insufficient to sustain high yields (Bijay-Singh et al., 2003; Yadvinder-Singh et al., 2005). Sulfur and micronutrient deficiencies are also emerging as significant limitations to productivity of the RWS (Shukla et al., 2009). Regional information on the benefit of sufficient K, S, and Zn application on productivity of the RWS in farmer's fields across the IGP is, however, scarce. We, therefore, conducted on-farm experiments with rice and wheat in northern India, representing a range of contrasting locations, to (i) determine attainable yields of rice and wheat with sufficient application of K and other nutrients; (ii) determine the response of rice and wheat to K, S, and Zn application; (iii) assess the financial return for use of fertilizer K, S, and Zn; and (iv) examine the effect of fertilization on soil N, P, K, S, and Zn status.

MATERIALS AND METHODS

The Study Region

On-farm experiments were conducted with rice and wheat during 2005–2006 in the Indian districts of Fatehgarh Sahib in the Punjab state; Meerut, Banda, and Barabanki in Uttar Pradesh; and Bhagalpur in Bihar (Fig. 1). Fatehgarh Sahib, Meerut, Barabanki, and Bhagalpur are located in the IGP where the RWS is a pre-dominant production system. Banda is located outside IGP where the RWS is an emerging production system. The locations chosen for the study represent diversity in soils, annual rainfall (450–1166 mm), and fertilizer use by farmers (Table 1).

The climate of Fatehgarh Sahib, located in the TGP, is arid subtropical with cool winters wherein temperatures occasionally drop below freezing point in the month of January. In summer, particularly in May, temperature rises up to 45°C. Soils of alluvial origin are Entisols and Inceptisols, deep, coarse-textured, well-drained, and low in organic C.

Meerut, located in the UGP, has a semiarid subtropical climate with dry hot summers and cold winters. Average maximum temperature is 45°C and average minimum temperature is 4.5°C. The soils of the experimental sites are sandy loam of Gangetic alluvial origin, very deep (>2 m), well-drained, and low in organic C. Banda has a subhumid climate with coarse-textured Entisols, low in CEC and organic C. The area is generally rainfed with extremely low crop productivity. The RWS is practiced in 0.61 million ha area where some irrigation is available during winter. Barabanki, located in the MGP, has a semiarid subtropical climate with dry hot summers and cold winters. The soils are of alluvial origin, very deep (>2 m), moderately to poorly drained, and classified as noncalcareous Udic Ustochrept. Bhagalpur is in the LGP and has a subhumid/subtropical climate with mild to hot summers and mildly cool to cool winters. Soils are very deep, poorly drained Eutrochrepts with high organic C.

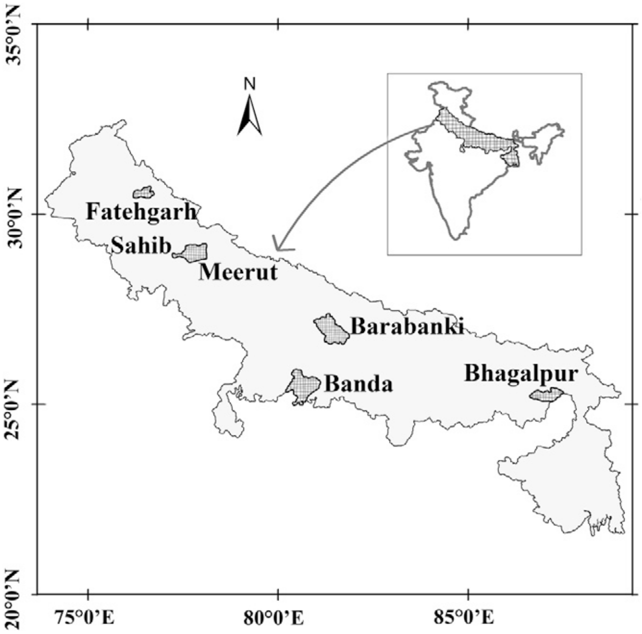

Fig. 1. Location of five districts in northern India with on-farm trials.

In each district, three villages with >80% of total cropped area under RWS, were selected for field experimentation following stratified random sampling technique. Cultivation of rice and wheat in rotation for more than 10 consecutive years was a criterion for selection of farmers' fields in these villages. This ensured the research findings were relevant to long-term RWS and not confounded by rotation and fertilizer management with other crops, such as sugarcane (*Saccharum officinarum* L.) or potato (*Solanum tuberosum* L.). Farmers of each experimental field were interviewed during May–June 2005 to record their current crop management practices, nutrient use, and rice and wheat production levels. All the surveyed farmers applied N and P fertilizer to both rice and wheat, although the application rates varied among the locations (Table 1). The rice and wheat yields also varied among the locations (Table 1), and the average annual production for the RWS (rice + wheat) was in the order: Fatehgarh Sahib > Meerut = Barabanki > Bhagalpur > Banda.

Treatments and Crop Management

Four fertilizer treatments: FFP, FFP with addition of K (+K), FFP with addition of K, S, and Zn (+KM), and FFP with addition of S and Zn (+M) were evaluated in 60 farmer's fields. In each field, the four treatments were randomly assigned to four 300 m^2 plots. In each of the five districts, one set of the

Table 1. Characteristics of farmer's fields with on-farm trials in the five districts in northern India.

Characteristics	Fatehgarh Sahib	Meerut	Banda	Barabanki	Bhagalpur
State	Punjab	Uttar Pradesh	Uttar Pradesh	Uttar Pradesh	Bihar
Location	30°38′ N, 76°27′ E	29°01′ N, 77°46′ E	25°20′ N, 80°22′ E	26°56′ N, 81°20′ E	25°15′ N, 87°01′ E
Elevation, m asl	259	237	118	125	43
Rainfall, mm	450	810	900	1050	1166
Farmer's fertilizer use for rice, kg ha^{-1}					
N	155 (6.6)†	156 (2.1)	87 (4.5)	150 (1.7)	73 (1.6)
P	15 (1.4)	25 (1.7)	13 (0.2)	18 (0.6)	15 (0.3)
K	0	0	0	8 (2.0)	0
Zn	2.0 (0.4)	2.0 (0.4)	0	1.8 (0.3)	0
Farmer's fertilizer use for wheat, kg ha^{-1}					
N	196 (7.2)	163 (2.2)	98 (4.1)	123 (4.9)	82 (1.5)
P	33 (4.0)	25 (0.3)	15 (0.2)	15 (0.5)	16 (0.37)
K	0	0	0	8 (2.0)	0
Zn	0	0	0	0	0
Farmer's rice yield, Mg ha^{-1}‡	5.9 (0.17)	4.9 (0.23)	2.7 (0.06)	5.0 (0.30)	3.5 (0.11)
Farmer's wheat yield, Mg ha^{-1}‡	4.5 (0.10)	4.0 (0.09)	2.3 (0.05)	3.6 (0.05)	2.3 (0.04)
Permanganate extractable N, mg kg^{-1}§	152 (5)	124 (4)	98 (3)	113 (4)	108 (5)
Bicarbonate extractable P, mg kg^{-1}§	12 (0.5)	9 (0.5)	9 (0.5)	10 (0.6)	9 (0.4)
Exchangeable K, mg kg^{-1}§	96 (9)	109 (5)	96 (5)	121 (5)	106 (7)
Non-exchangeable K, mg kg^{-1}§	2607 (37)	2385 (45)	1353 (28)	2384 (82)	2480 (118)
Extractable S, mg kg^{-1}§	9 (0.9)	13 (0.7)	11 (0.6)	11 (0.8)	10 (0.8)
DTPA-extractable Zn, mg kg^{-1}§	0.8 (0.04)	0.8 (0.04)	0.7 (0.06)	0.8 (0.07)	0.8 (0.10)
Soil texture	sandy loam to loamy sand	sandy loam to loamy sand	silty clay loam to loamy clay	clay loam to loamy clay	clay loam to silty clay loam

† Values in parenthesis are standard error of the mean (number of observations = 12).

‡ Mean yield measured in this study in field plots with farmer's management practices.

§ Available N determined by alkaline $KMNO_4$ extraction; Olsen P determined by extraction with 0.5 M $NaHCO_3$ at pH 8.5; exchangeable K determined by extraction with 1 M NH_4OAc at pH 7; non-exchangeable K determined by extraction with 1 M HNO_3; extractable S determined by extraction with 0.15% $CaCl_2$; and DTPA-extractable Zn determined by extraction with DTPA-$CaCl_2$–TEA at pH 7.3.

four treatments was conducted in 12 farmer's fields—four in each of three villages. In +K and +KM plots, K as KCl was applied at 63 kg K ha^{-1} to rice as well as wheat. For rice, K was applied as 50% basal and 50% at about 50 d after transplanting, whereas for wheat all K was applied as basal. The S was applied as elemental S powder (80% S) at 30 kg S ha^{-1} to both rice and wheat, and Zn was applied as zinc sulfate (21% Zn) at 5 kg Zn ha^{-1} to only rice. Both S and Zn were applied basal at the time of crop establishment. The existing FFP for N and P was followed in all four treatments for rice and wheat.

We used the treatment with applied S and Zn (+M) as the equivalent of a K-omission plot capable of assessing the K-limited yield, because farmers typically applied sufficient fertilizer N and P but no fertilizer K to their fields (Table 1). The treatment to which we applied K served as an omission plot for S plus Zn capable of assessing soil indigenous S and Zn supply based on yield of rice and wheat. It cannot be ascertained from our study whether the yield gain from S + Zn arose from the added S, Zn, or both S and Zn.

Except for fertilizer application, farmers used their own practices and resources for growing the crops. Twenty five-day-old seedlings of rice cultivar PHB 71 using 2 seedlings $hill^{-1}$ were transplanted at 20 to 30 hills m^{-2} during 13 to 26 June at Fatehgarh Sahib, 1 to 20 July at Meerut, 5 to 15 August at Banda, 4 to 18 July at Barabanki, and 2 to 19 August at Bhagalpur. Farmers managed weeds in rice with one or two manual weedings at Banda, Barabanki, and Bhagalpur. Butachlor (N-butoxymethyl-2-chloro-2',6'-diethylacetanilide) was applied at 2.5 L ha^{-1} at Fatehgarh Sahib and Meerut, followed by one manual weeding. Rice was grown with irrigation. Climate parameters, number of irrigations, and total amount of irrigation water applied for the rice cropping period at each location are shown in Table 2. Rice was harvested manually retaining only 10 to 15 cm of standing biomass during the first week of October at Fatehgarh Sahib, last week of October at Meerut and Barabanki, and the second half of November at Bhagalpur and Banda.

After rice, the land was tilled three to four times to a 15-cm depth with a tractor-drawn harrow and cultivator at Fatehgarh Sahib and Meerut, whereas at Banda, Barabanki, and Bhagalpur land was tilled five to seven times with a cultivator. The succeeding wheat, cultivar PBW 343, was sown on the same plots during 2 to 11 November at Fatehgarh Sahib, 2 to 6 November at Meerut, 14 to 29 December at Banda, 23 November to 12 December at Barabanki, and 1 to 7 December at Bhagalpur. Wheat was sown at 100 kg seed ha^{-1} by a tractor drawn seed drill in rows 20-cm apart at Fatehgarh Sahib. At other locations, it was sown by broadcasting and then a wooden plank was drawn over the field to cover the seed. The crop received one to six irrigations depending on the location (Table 2). Wheat was harvested manually retaining 5 cm

Table 2. Climate parameters and irrigation during the rice and wheat cropping season at five locations in northern India.

Parameter	Fatehgarh Sahib	Meerut	Banda	Barabanki	Bhagalpur
Rice cropping season					
Maximum daily temperature, °C	34.1 (25.4–44.2)†	33.4 (27.0–40.9)	32.7 (25.6–45.4)	34.3 (25.5–45.4)	30.2 (21.6–36.0)
Minimum daily temperature, °C	23.5 (10.2–31.2)	22.9 (13.0–27.0)	22.1 (8.0–31.7)	25.6 (18.5–29.0)	22.1 (7.5–28.5)
Rainfall, mm	560	816	460	804	1031
Sunshine hours, h d^{-1}	8.2	6.0	5.2	6.6	5.9
Number of irrigations	24 (22–28)	14 (11–19)	3.8 (3–5)	4.9 (4–6)	4.2 (4–6)
Total irrigation water applied, mm	1560 (1430–1820)	1050 (770–1530)	220 (170–290)	310 (250–440)	290 (280–400)
Wheat cropping season					
Maximum daily temperature, °C	24.8 (13.6–37.0)	26.3 (6.0–37.8)	27.6 (19.0–38.8)	28.5 (18.0–39.5)	27.5 (18.5–38.0)
Minimum daily temperature, °C	9.3 (−0.6–21.6)	9.1 (1.0–17.5)	11.1 (2.2–20.5)	10.3 (1.0–22.5)	12.1 (3.5–21.9)
Rainfall, mm	55	82	6	6	6
Sunshine hours, h d^{-1}	7.8	7.1	7.9	7.7	7.4
Number of irrigations	4 (3–5)	4.9 (4–6)	1.6 (1–2)	3.9 (3–4)	3 (3)
Total irrigation water applied, mm	260 (190–320)	290 (230–330)	110 (80–150)	230 (180–240)	180 (170–200)

† Values in parenthesis represent the range from minimum to maximum during the cropping season.

of standing stubbles during the first half of April 2006 at all locations.

Grain and straw yields of rice and wheat were determined from 10 m^2 in each plot, comprising four predetermined 2.5 m^2 harvest areas within each plot. After sun-drying for 3 d in the field, the total biomass (grain + straw) was weighed and threshed with a plot thresher. Grain yields are reported at a water content of 140 g kg^{-1} for rice and wheat. Straw yields were reported on dry weight basis. Ten representative panicles of rice were randomly selected from each plot for determination of number of filled and unfilled grains $panicle^{-1}$, and 10 representative spikes of wheat were selected from each plot for determination of number of grains $spike^{-1}$.

Soil and Plant Analysis

Soil samples were collected at 0- to 15-cm depth from five places in each of the 60 farmer's fields before commencement of the experiment in 2005. Soil samples at 0- to 15-cm depth were also collected from each plot after wheat harvest in 2006. Soil samples collected from each field were composited and mixed; a subsample was pulverized using a wooden pestle and mortar and passed through a 100-mm sieve. Soils were analyzed for extractable N by the alkaline $KMNO_4$ method (Subbiah and Asija,1956), extractable P (0.5 M $NaHCO_3$, pH 8.5 extraction) (Olsen et al., 1954), exchangeable K (1 M NH_4OAc, pH 7.0 extraction) (Helmke and Sparks, 1996), non-exchangeable K (1 M HNO_3 extraction) (Helmke and Sparks, 1996), extractable S (0.15% $CaCl_2$ extraction) (Williams and Steinbergs, 1959), and DTPA-extractable Zn (DTPA-$CaCl_2$–TEA at pH 7.3 extraction) (Lindsay and Norvell, 1978). Particle size analysis was conducted by the pipette method on initial soil samples. Means for initial soil properties for each district are reported in Table 1.

Representative subsamples of grain and straw of rice and wheat were dried at 70°C, ground in a stainless steel Wiley mill, and then wet digested with concentrated H_2SO_4 for determination of total N, or digested with concentrated HNO_3 and $HClO_4$ (mixed in 4:1 ratio) for determination of total P, K, S, and Zn. The N content was determined by the Kjeldahl method using an auto analyzer, P was determined by the vanadomolybdate yellow color method (Piper, 1966), and S was determined turbidimetrically (Chesnin and Yien, 1951) using an ultraviolet–visible (UV–VIS) spectrophotometer. Total K content was determined by flame photometry. Zinc was determined with an atomic absorption spectrophotometer.

Financial Analysis

Added net return for fertilization with K, S, and Zn relative to FFP was determined using prices of rice grain (U.S.$ 0.19 kg^{-1}), rice straw (U.S.$ 0.01 kg^{-1}), wheat grain (U.S.$ 0.23 kg^{-1}), and wheat straw (U.S.$ 0.06 kg^{-1}) and costs of fertilizers. The costs of fertilizer on a nutrient basis were N = U.S.$ 0.23 kg^{-1}, P = U.S.$ 0.36 kg^{-1}, K = U.S.$ 0.20 kg^{-1}, S = U.S.$ 0.26 kg^{-1}, and Zn = U.S.$ 0.67 kg^{-1}. The total cost of fertilizer for a treatment was computed as the sum of costs for each applied nutrient. The prices of rice and wheat grain reflect the minimum support prices fixed by the government. The prices of rice and wheat straw reflect prevailing prices in local markets averaged across locations at the time of harvest. Fertilizer prices are from FAI (2011). Soil testing services are often available to farmers at very low cost due to subsidies. The cost of soil testing was consequently not considered in the financial analysis. Use of K, S, and Zn fertilizers does not involve added cost for application because they would be applied at the same time as existing N or P fertilizers.

Comparisons of yield for the entire RWS were made on rice equivalent yield for systems (SREY):

$$\text{SREY} = Y_R + [(Y_W \times P_W)/P_R]$$

where Y_R = rice grain yield in kg ha^{-1}, Y_W = wheat grain yield in kg ha^{-1}, P_R = price of rice in U.S.$ kg^{-1}, and P_W = price of wheat in U.S.$ kg^{-1}

Statistical Analysis and Computations

Data were analyzed across locations (districts) to determine the effects of fertilizer treatment, location, and fertilizer treatment × location interaction on performance of rice and wheat, net financial returns, soil properties, and changes in soil nutrients. Homogeneity of variance for all variables was first tested to ensure that residual errors have identical variances across all treatment groups (Littell et al., 2006). Normality of the residuals was tested using the Shapiro–Wilk statistic obtained from the NORMAL option in the PROC UNIVARIATE statement (SAS Institute, 2010), and data were transformed as required for analysis. Among the dependent variables, rice grain Zn, exchangeable K, non-exchangeable K, change in exchangeable K, and change in extractable S were analyzed using a model with a pooled error variance.

Data were separated by five locations (districts) and four fertilizer treatments within each of 12 farms per location. Analysis of variance for a randomized complete block design with subsampling was performed using the MIXED procedure of SAS version 9.1.2 (SAS Institute, 2003) where location was the blocking factor and each farmer's field was treated as a subsample. In these analyses, fertilizer treatment, location, and fertilizer treatment × location interaction were considered as fixed factors while fertilizer treatment × location interaction was considered as the random factor. Comparisons among treatment means were determined using the Tukey–Kramer method at $\alpha = 0.05$.

The effects of application of K (+K), application of S + Zn (+M) and K × M × location interaction were tested using contrast analyses. When K × M × location interaction was not significant the average of the means of treatments FFP and +M were subtracted from the average of the means of treatments +K and +KM to extract the effect of K, and the average of the means of treatments FFP and +K were subtracted from the average of the means of treatments +M and +KM to extract the effect of M. The mention of significance refers to the 5% level of probability ($\alpha = 0.05$) unless otherwise specified.

Reciprocal internal efficiency (RIE) of N, P, or K was computed as the amount of N, P, or K in the aboveground plant dry matter Mg^{-1} of grain production. Harvest index (HI) expressed grain yield as a proportion of total aboveground dry matter—kg grain kg^{-1} total aboveground dry matter.

RESULTS AND DISCUSSION

Performance of Rice

Effect of Potassium

Our findings on the fertilizer practices of farmers (Table 1) support findings of earlier surveys (Sharma, 2003) that farmers typically applied ample N and P to rice and wheat, while largely ignoring application of other nutrients particularly K. Rice yield with FFP ranged from 5.9 Mg ha^{-1} at Fatehgarh Sahib to 2.7 Mg ha^{-1} at Banda (Table 1). High rice yield at Fatehgarh Sahib probably associated with ample supply of irrigation water and high sunshine hours (Table 2). The number of irrigations and amount of applied irrigation water were much less at Banda, Barabanki, and Bhagalpur. Low yield at Banda probably results from shortage of water at transplanting and sufficient irrigation to overcome water deficits at this location with lowest rainfall (Table 2).

Application of only K increased rice grain yield ($P \leq 0.001$) across all locations (Table 3) regardless of the large differences in soil texture, exchangeable and non-exchangeable K (Table 1), climate, and irrigation (Table 2) across locations. The increase from only K was 0.6 Mg ha^{-1} each at Fatehgarh Sahib and Barabanki, 0.9 Mg ha^{-1} at Meerut, 1 Mg ha^{-1} at Banda, and

Table 3. Effect of K and S plus Zn (M) on rice grain yield, performance of rice and wheat, and rice equivalent yield for a rice–wheat system (SREY) at five locations in northern India. The K × M × location interaction was significant at $P \leq 0.05$ for all listed parameters.

	Fatehgarh Sahib			Meerut			Banda			Barabanki			Bhagalpur		
Parameter	**No M**	**+M**	**Diff†**	**No M**	**+M**	**Diff**	**No M**	**+M**	**Diff**	**No M**	**+M**	**Diff**	**No M**	**+M**	**Diff**
Rice grain yield, Mg ha^{-1}															
No K	5.9	6.6	0.7**	4.9	5.5	0.6***	2.7	3.3	0.6***	5.0	5.4	0.4***	3.5	4.3	0.9***
+K	6.5	7.0	0.5*	5.7	6.1	0.4***	3.7	4.1	0.4***	5.6	5.9	0.3***	4.6	4.9	0.2***
Difference‡	0.6***	0.4*		0.9***	0.6***		1.0***	0.7***		0.6***	0.5***		1.2***	0.5***	
Rice grains per panicle (no.)															
No K	91	97	6ns§	64	69	5***	97	105	8***	108	110	3**	81	86	5***
+K	98	104	6**	69	72	3***	118	128	10***	112	115	3***	88	90	1***
Difference	7**	7*		5**	3***		22***	23***		5***	5***		8***	4***	
Total K in rice, kg ha^{-1}															
No K	108	122	14**	102	114	12***	56	66	11***	98	101	3ns	74	90	16***
+K	130	140	10**	130	137	7***	80	87	7***	119	127	8***	103	109	6***
Difference	23***	18***		27***	22***		24***	21***		21***	26***		29***	20***	
Wheat grains per spike (no.)															
No K	44	46	2.5***	40	44	4.4***	41	43	1.6***	38	39	1.6***	39	42	3.0***
+K	46	49	3.2***	46	48	2.2***	43	46	2.7***	40	41	1.4**	45	47	2.5***
Difference	1.7***	2.4***		6.0***	3.8***		2.0***	3.1***		2.2***	2.0***		5.3***	4.8***	
SREY, Mg ha^{-1}															
No K	11.7	12.6	0.9***	10.0	11.2	1.2***	5.7	6.8	1.0***	9.5	10.3	0.7***	6.4	7.7	1.3***
+K	12.5	13.2	0.7**	11.8	12.6	0.8***	7.2	8.0	0.8***	10.6	11.2	0.6***	8.4	9.1	0.7***
Difference	0.8***	0.6**		1.8***	1.4***		1.5***	1.3***		1.1***	0.9***		2.1***	1.4***	

* Significant at $P \leq 0.05$.

** Significant at $P \leq 0.01$.

*** Significant at $P \leq 0.001$.

† Diff = Difference between non-rounded treatment means for no added S + Zn (no M) and added S + Zn (+M).

‡ Difference = Difference between non-rounded treatment means for no added K (no K) and added K (+K).

§ ns = Not significant at $P \leq 0.05$.

Table 4. Effect of K and S plus Zn (M) application on grain filling and uptake of nutrients by rice and grain yield and the uptake of nutrients for wheat at five locations in northern India. The K × M × location interaction was not significant at $P \leq 0.05$ for all the listed parameters.

Parameter	Fatehgarh Sahib	Meerut	Banda	Barabanki	Bhagalpur
Rice unfilled grain, %					
No K	12	10	11	10	12
+K	10	6	5	8	10
Difference†	–1.8ns‡	–4.5***	–5.4***	–1.3*	–2.7***
No M	12	9	9	10	11
+M	9	7	7	9	11
Difference§	–2.9***	–2.3***	–1.7**	–1.0ns	–1.0ns
Total S in rice, kg ha^{-1}					
No K	24	23	12	20	15
+K	26	25	15	22	17
Difference	1.3***	2.2***	2.8***	1.7**	2.4***
No M	20	20	10	16	12
+M	30	28	17	25	21
Difference	10.8***	8.4***	7.4***	9.1***	9.3***
Rice grain Zn, mg kg^{-1}					
No K	32	32	34	31	33
+K	32	32	34	32	34
Difference	0.2ns	0.2ns	0.0ns	0.7*	0.9**
No M	29	30	30	28	30
+M	35	35	38	34	37
Difference	6.3***	5.2***	7.3***	6.0***	6.3***
Wheat grain yield, Mg ha^{-1}					
No K	4.6	4.3	2.5	3.7	2.5
+K	4.8	5.0	2.9	4.1	3.2
Difference	0.2***	0.7***	0.4***	0.3***	0.7***
No M	4.6	4.4	2.6	3.8	2.6
+M	4.8	4.8	2.9	4.0	3.0
Difference	0.2***	0.4***	0.3***	0.3***	0.4***
Total K in wheat, kg ha^{-1}					
No K	101	80	51	74	50
+K	114	99	64	93	68
Difference	13.8***	18.7***	13.3***	19.8***	17.8***
No M	108	86	55	81	56
+M	107	93	60	86	62
Difference	–0.1ns	7.5***	5.8***	4.1**	6.4***
Total S in wheat, kg ha^{-1}					
No K	25	23	13	18	13
+K	26	27	14	20	16
Difference	0.4*	3.7***	1.8***	1.9***	3.7***
No M	20	20	10	15	11
+M	31	29	17	24	18
Difference	11.4***	9.0***	6.9***	9.8***	6.7***
Wheat grain Zn, mg kg^{-1}					
No K	30	31	33	30	32
+K	30	31	33	30	33
Difference	0.5ns	0.4ns	0.3ns	–0.1ns	0.3ns
No M	27	29	29	26	29
+M	33	34	37	34	36
Difference	5.7***	5.0***	7.8***	7.4***	6.8***

* = Significant at $P \leq 0.05$.

** = Significant at $P \leq 0.01$.

*** = Significant at $P \leq 0.001$.

† Difference between non-rounded means for two no K treatments (no application of K, S, or Zn and application of S + Zn) and two +K treatments (application of K only and application of K with S + Zn).

‡ ns = Not significant at $P \leq 0.05$.

§ Difference between non-rounded means for two no M treatments (no application of K, S, or Zn and application of K only) and two +M treatments (application of S + Zn only and application of K with S + Zn).

1.2 Mg ha^{-1} at Bhagalpur. The increase from applied K, when S and Zn were present (+M), was 0.4 to 0.7 Mg ha^{-1} across the locations. The significant increase in rice yield due to K application is contrary to the earlier belief that release of native K from illitic clay minerals of the IGP soils is sufficient to meet the K needs of the crops (Bijay-Singh et al., 2003). The increase in yield from added K is however consistent with reports that application of K has become essential for sustaining high yields in the IGP (Regmi et al., 2002).

The increase in rice yield due to application of K was associated with increased number of grains per panicle (Table 3) and a reduced percentage of unfilled grains (Table 4). The positive effects of K application on rice might have also benefited from the split application of K (50% basal and 50% at about 50 d after transplanting). Potassium plays a vital role in translocation of photosynthates from source to sink at panicle initiation and heading (Tiwari et al., 1992).

Application of 63 kg K ha^{-1} significantly increased total K (Table 3) and S (Table 4) as well as total N, P, and Zn (data not shown) in the rice plant at maturity. Application of K increased total plant K at maturity ($P \leq 0.001$) by 21 to 29 kg ha^{-1} across the five locations (Table 3). The increase in total plant S ranged from 1.3 to 2.8 kg ha^{-1} (Table 4). The corresponding increases in total plant nutrients from application of K ranged from 3 to 24 kg ha^{-1} for N, 1.2 to 3.1 kg ha^{-1} for P, and 25 to 59 g kg^{-1} for Zn (data not shown). The increased uptake of Zn by rice had little effect on Zn concentration in unmilled rice grain (Table 4).

The increases from added K in total plant nutrients at maturity reflect increased grain yield and biomass production with application of K. The increase in plant N from added K (3 to 35%) paralleled the increase in rice grain yield (6 to 34%) across the locations. The increase in plant K from added K (15 to 43%) was, however, consistently higher than the increase in grain yield from added K, presumably because of K limitations on growth in the absence of added K and potentially luxuriant uptake of K in the presence of added K.

Effect of Sulfur Plus Zinc

Application of S plus Zn (+M) with and without application of K increased rice yield by 0.2 to 0.9 Mg ha^{-1} across the locations (Table 3). The increase in rice yield due to S + Zn was associated with increased number of grains per panicle (Table 3) and a reduced percentage of unfilled grains (Table 4). These findings of gains in rice yield from application of S + Zn match reports of widespread deficiencies of these nutrients in Indian soils (Singh et al., 2008; Shukla and Behra, 2011).

Annual removal of 25 to 54 kg S ha^{-1} has been estimated in the high yielding RWS (Tandon, 2011). Increased use of diammonium phosphate rather than traditional S-containing fertilizers like ammonium sulfate and single superphosphate contributes to insufficient replenishment of S through fertilizers. Yield gains for rice from Zn application have been widely reported (Shukla et al., 2009) and the magnitude of Zn deficiencies has been reported to be greater than S deficiencies in India (Shukla and Behra, 2011). Recent reports, however, indicate a decline in the extent of Zn deficiency in soils of Punjab due to use of Zn fertilization (Shukla and Behra, 2011). In our study, farmers at Fatehgarh Sahib in Punjab and at Meerut and Barabanki in Uttar Pradesh were applying Zn to rice (Table 1).

Application of 30 kg S ha^{-1} plus 5 kg Zn ha^{-1} to rice increased total K (Table 3) and S (Table 4) as well as total N, P, and Zn (data not shown) in the rice plant at maturity. Application of S + Zn increased total plant S at maturity ($P \leq 0.001$) by 7.4 to 10.8 kg ha^{-1} across the five locations (Table 4). Application of S + Zn increased total plant Zn at maturity ($P \leq 0.001$) by 76 to 103 g ha^{-1} across the five locations (data not shown). This increase in plant Zn corresponded to increases ($P \leq 0.001$) of 5.2 to 7.3 mg kg^{-1} in Zn concentration in unmilled rice grain across the five locations (Table 4). Balanced fertilization involving Zn application can help increase the nutritional quality of grain as well as yield. This is consistent with other reports of Zn enrichment of rice grain due to Zn fertilization (Shivay et al., 2008).

The increases in total plant nutrients from application of S + Zn ranged from 5 to 19 kg ha^{-1} for N, 1.5 to 3.5 kg ha^{-1} for P, and 3 to 16 kg kg^{-1} for K (data not shown). The increases from added S + Zn in total plant nutrients at maturity reflect increased grain yield and biomass production with application of S + Zn. Our findings are consistent with reports that balanced fertilizer use, which overcomes deficiency of secondary nutrients and micronutrients, can increase crop yield and use efficiency of macronutrients (N, P, and K) (Dwivedi et al., 2011).

The increase in grain yield from applied S + Zn tended to be less with added K (+K) than without added K (no K), just as the increase in grain yield from applied K tended to be less with added S + Zn (+M) than without added S + Zn (no M) (Table 3). This lower yield gain from an added nutrient in the presence than absence of the other nutrient reflects reduced increases in yield as yield approaches an upper limit, which is determined by climate and management factors. As nutrient constraints are removed, factors other than nutrients can be expected to increasingly constrain the attainable yield.

Highest yields were obtained when K was applied with S + Zn (Table 3). The combined application of K, S, and Zn as compared to FFP increased rice grain yield by 1.1 Mg ha^{-1} at Fatehgarh Sahib, 1.2 Mg ha^{-1} at Meerut, 1.4 Mg ha^{-1} at Banda, 0.9 Mg ha^{-1} at Barabanki, and 1.4 Mg ha^{-1} at Bhagalpur. Rice grain yield increased by 0.2 to 0.5 Mg ha^{-1} across the five locations when the application of K was combined with application of S + Zn (Table 3). Other studies have highlighted K, S, and Zn deficiencies for rice in on-station and researcher-managed trials in the IGP (Singh et al., 2008), but our study is one of the few studies to document the benefits of K, S, and Zn in farmer's fields across the IGP from Punjab to Bihar.

Performance of Wheat

Farmers in our study applied K to wheat only at Barabanki and did not apply Zn to wheat at any of the locations (Table 1). Wheat yield with FFP ranged from 4.5 Mg ha^{-1} at Fatehgarh Sahib to 2.3 Mg ha^{-1} at Banda and Bhagalpur (Table 1). High wheat yield at Fatehgarh Sahib was probably associated with early sowing (2–11 November) and subsequent lower temperatures at critical growth stages combined with ample irrigation water (Table 2). Low yield at Banda and Bhagalpur probably resulted from late sowing (14–29 December at Banda and 1–7 December at Bhagalpur) and subsequent higher temperatures at critical growth stages. Wheat sowing was delayed at Banda due to water shortage, and wheat yield at Banda was also limited by insufficient irrigation (Table 2).

Application of 63 kg K ha^{-1} to wheat following application of the same quantity of K to rice significantly increased ($P \leq 0.001$) wheat yield across all locations regardless of differences in soil texture, exchangeable and non-exchangeable K (Table 1), climate, and irrigation (Table 2) across locations. Applied K increased yield by 0.2 Mg ha^{-1} at Fatehgarh Sahib, and 0.7 Mg ha^{-1} each at Meerut and Bhagalpur, 0.4 Mg ha^{-1} at Banda, and 0.3 Mg ha^{-1} at Barabanki (Table 4). The increase in wheat yield due to K fertilization was associated with increased number of wheat grains per spike (two–six) across locations (Table 3). Differences among locations in yield gain from application of K to wheat (Table 4), as well as to rice (Table 3), likely arise from differences in soil (Table 1), crop yield, and retention of crop residues.

Application of K increased ($P \leq 0.001$) total K in the wheat plant at maturity by 13 to 20 kg K ha^{-1}. The corresponding increases in other plant nutrients from application of K were 5 to 13 kg ha^{-1} for N, 1.2 to 2.5 kg ha^{-1} for P (data not shown), 0.4 to 3.7 kg ha^{-1} for S (Table 4), and 4 to 43 g ha^{-1} for Zn (data not shown). The increases from added K in total plant nutrients at maturity reflect increased grain yield and biomass production with application of K. The increase in plant Zn from application of K did not increase Zn concentration in unmilled wheat grain (Table 4).

Application of S + Zn to the preceding rice and then 30 kg S ha^{-1} to wheat (+M) significantly improved ($P \leq 0.001$) wheat yield by 0.2 Mg ha^{-1} at Fatehgarh Sahib, and 0.4 Mg ha^{-1} each at Meerut and Bhagalpur, and 0.3 Mg ha^{-1} each at Banda and Barabanki (Table 4). The increase in wheat yield was associated with increased number of wheat grain per spike (1.4 to 4.4) across locations (Table 3).

Table 5. Effect of K and S plus Zn (M) application on added net return for rice and wheat relative to the farmer's fertilizer practice without added K or M in a rice–wheat system at five locations in northern India.

		Added net return from added nutrients				
Crop	Treatment	Fatehgarh Sahib	Meerut	Banda	Barabanki	Bhagalpur
		U.S.\$ ha^{-1}				
Rice	+K	119a†	174b	191b	114b	233b
Rice	+KM	217a	248a	267a	175a	281a
Rice	+M	135a	126c	120c	72c	172c
Wheat	+K	29b	212b	115b	101b	214b
Wheat	+KM	59a	311a	214a	175a	320a
Wheat	+M	38ab	134c	100b	74c	110c

† Means within a column for a crop followed by the same letter are not significantly different according to Tukey–Kramer test at $\alpha = 0.05$.

Table 6. Effect of potassium (K) and sulfur plus zinc (M) application on soil properties after the wheat crop in a rice–wheat rotation at five locations in northern India. The K × M × location interaction was not significant at $P \leq 0.05$ for all the listed parameters.

Parameter	Fatehgarh Sahib	Meerut	Banda	Barabanki	Bhagalpur
Permanganate extractable N, mg kg^{-1}					
No K	165	136	107	122	117
+K	151	132	97	115	111
Difference†	−14***	−4ns‡	−9***	−7**	−6***
No M	163	135	104	121	114
+M	154	133	100	116	114
Difference§	−9***	−2ns	−3**	−4***	1ns
Bicarbonate extractable P, mg kg^{-1}					
No K	13	10	11	11	10
+K	12	9	10	10	10
Difference	−0.9***	−0.9***	−0.8***	−1.2**	−0.2*
No M	13	10	10	10	10
+M	12	9	10	10	10
Difference	−0.3**	−0.1ns	−0.5***	−0.5***	−0.3**
Exchangeable K, mg kg^{-1}					
No K	89	102	90	113	96
+K	102	116	103	129	114
Difference	13***	13***	14***	17***	17***
No M	96	110	98	122	106
+M	94	109	95	120	104
Difference	−2***	−1ns	−3***	−3***	−3ns
Non-exchangeable K, mg kg^{-1}					
No K	2577	2363	1334	2358	2462
+K	2618	2394	1360	2398	2494
Difference	41***	31***	26**	40***	33**
No M	2600	2380	1348	2382	2479
+M	2596	2378	1346	2374	2477
Difference	−4*	−2ns	−2ns	−8ns	−3ns
Extractable S, mg kg^{-1}					
No K	10	13	12	11	11
+K	10	12	12	11	10
Difference	−0.4***	−1.0***	−0.4**	−0.6***	−0.4**
No M	8	11	11	9	9
+M	11	15	14	13	12
Difference	2.8***	3.3***	3.2***	3.6***	3.0***
DTPA extractable Zn, mg kg^{-1}					
No K	0.8	0.8	0.7	0.8	0.8
+K	0.8	0.8	0.7	0.7	0.8
Difference	−0.03***	−0.04***	−0.02***	−0.03***	−0.02***
No M	0.7	0.7	0.7	0.7	0.7
+M	0.8	0.8	0.8	0.8	0.8
Difference	0.11***	0.14***	0.11***	0.11***	0.12***

* Significant at $P \leq 0.05$.

** Significant at $P \leq 0.01$.

*** Significant at $P \leq 0.001$.

† Difference between non-rounded means for two no K treatments (no application of K, S, or Zn and application of S + Zn) and two +K treatments (application of K only and application of K with S + Zn).

‡ ns = Not significant at $P \leq 0.05$.

§ Difference between non-rounded means for two no M treatments (no application of K, S, or Zn and application of K only) and two +M treatments (application of S + Zn only and application of K with S + Zn).

The application of S to wheat increased total S in the wheat plant at maturity by 6.7 to 11 kg ha^{-1} (Table 4). The corresponding increases in other plant nutrients from application of S + Zn were 5 to 8 kg ha^{-1} for N, 1.2 to 1.8 kg ha^{-1} for P (data not shown), 0 to 7.5 kg ha^{-1} for K (Table 4), and 59 to 72 g ha^{-1} for Zn (data not shown). The increase in plant Zn corresponded to increases ($P \leq 0.001$) of 5.0 to 7.8 mg kg^{-1} in Zn concentration in unmilled wheat grain across the five locations (Table 4). Our findings indicate the residual effect of Zn applied to rice can be sufficient to increase Zn in grain of the subsequent wheat crop.

System Performance and Financial Returns

The productivity of the RWS measured in terms of SREY was lowest at Banda and Bhagalpur (Table 3). Late sowing of wheat contributed to low wheat yields at Banda and Bhagalpur, and insufficient irrigation water reduced rice and wheat yields at Banda. Regardless of these constraints and differences in climate and irrigation among locations (Table 2), SREY increased significantly with application of K or S + Zn at all the locations (Table 3). Application of K increased SREY by 0.6 to 2.1 Mg ha^{-1}, and application of S + Zn increased SREY by 0.6 to 1.3 Mg ha^{-1}. Combined application of the three nutrients (K, S, and Zn) increased SREY from 1.5 Mg ha^{-1} for Fatehgarh Sahib to 2.7 Mg ha^{-1} for Bhagalpur (Table 3).

Yield gain to application of secondary nutrients and micronutrients can be negligible under severe K deficiency (Hegde and Dwivedi, 1992), but the soils at the locations in our study had intermediate K fertility (96–121 mg kg^{-1} exchangeable K). The soil K supply at the locations was sufficient to support further increases in yield from application of S + Zn without K fertilization. Even though rice and wheat at all locations responded to K application, rice yields and SREY (Table 3) increased with application of only S + Zn without added K at all locations.

The soils at the locations in our study were not severely deficient in extractable S and Zn (Table 1). The soil supply of S and Zn at the locations was sufficient to support further increases in yield from application of only K fertilizer, as evidenced by increase in rice yields and SREY with application of only K without added S + Zn at all locations.

The SREY for FFP (no K, no M) and the effects of fertilization on SREY (Table 3) were not clearly associated with initial soil fertility reported in Table 1. The SREY was highest at Fatehgarh Sahib and the increase in SREY from application of K was lowest at Fatehgarh Sahib (Table 3) even though Fatehgarh Sahib had the lowest exchangeable K (96 mg kg^{-1}) (Table 1). Bhagalpur did not have markedly lower exchangeable K, extractable S, or extractable Zn than other locations even though it had the largest increase in SREY from the combined application of K, S, and Zn.

Added fertilizer input cost for rice was U.S.$ 12.4 ha^{-1} for K, U.S.$ 7.7 ha^{-1} for S, and U.S.$ 16.7 ha^{-1} for Zn. Added fertilizer input cost for wheat was U.S.$ 12.4 ha^{-1} for K and U.S.$ 7.7 ha^{-1} for S. This added cost was small compared to the value of the increased yield, and the added net return from applied K and S + Zn was positive for rice and wheat at all locations (Table 5). Added net return for rice was lowest for application of only S + Zn (without K) and highest for application K with S + Zn across all locations except Fatehgarh Sahib.

Added net return in wheat was similarly highest for application of K with S + Zn across all locations except Fatehgarh Sahib (Table 5). Added net return for wheat was greater from application of only K than only S + Zn at all locations except Fatehgarh Sahib and Banda. Although yields and yield gains from added nutrients tended to be lower for wheat than rice, the added net return remained high for wheat because of higher value of grain and straw for wheat than for rice and lower fertilizer cost for wheat as Zn was not applied to wheat.

Soil Nutrient Status

After One Rice–Wheat Cycle

Soil properties were measured after wheat to determine the effect of K and S + Zn (+M) applications after one rice–wheat cropping cycle (Table 6). Application of K consistently reduced permanganate-extractable N, bicarbonate-extractable P, extractable S, and DTPA-extractable Zn after the wheat crop at all locations. The decline in N, P, S, and Zn was associated with increased yields of rice (Table 3) and wheat (Table 4) and the associated increased uptake of these nutrients by the crops. Lower permanganate-extractable N has been reported in plus K than minus K treatments in long-term experiments with the RWS (Hegde and Dwivedi, 1992). Application of K increased exchangeable and non-exchangeable K (Table 6), and the increase was relatively greater in non-exchangeable K (26 to 41 mg kg^{-1}) as compared to exchangeable K (13 to 17 mg kg^{-1}).

Application of S + Zn (+M) often reduced permanganate-extractable N, bicarbonate-extractable P, and exchangeable K; but it had little effect on non-exchangeable K (Table 6). The decline in N, P, and exchangeable K was associated with increased yields of rice (Table 3) and wheat (Table 4) and the associated increased uptake of these nutrients by the crops. Application of S + Zn increased ($P \le 0.001$) extractable S by 2.8 to 3.6 mg kg^{-1} across the locations and increased extractable Zn by 0.11 to 0.14 mg kg^{-1} across the locations (Table 6). These increases in extractable soil S and Zn reflect the application of these nutrients in excess of the removal of the nutrients in harvested grain and straw.

Change during One Rice–Wheat Cycle

Soil properties before the rice crop and after the wheat crop were used to determine change during one rice–wheat cropping cycle (Table 7). In the absence of added K, exchangeable K decreased by 6 to 9 mg kg^{-1} and non-exchangeable K decreased by 18 to 30 mg kg^{-1} during one rice–wheat cropping cycle. With application of K, exchangeable K increased by 6 to 9 mg kg^{-1} and non-exchangeable K increased by 7 to 14 mg kg^{-1}. The difference between application of K and the farmer's practice without the added K after one rice–wheat cropping cycle ranged from 13 to 18 mg kg^{-1} for exchangeable K and 26 to 41 mg kg^{-1} for non-exchangeable K across the locations (Table 7).

The decline in soil K without added K (Table 7) highlights the risk of rapid short-term mining of soil K with the farmer's current practice of using relatively high rates of N and P with little or no use of K. Long-term cropping with negative K balances has been associated with yield declines in the RWS in South Asia and China (Regmi et al., 2002; Bijay-Singh et al., 2003). The K balances were negative even with recommended rates of K, and were least negative when farmyard manure was a nutrient source or wheat residues were returned (Regmi et al., 2002; Bijay-Singh et al., 2003). Although the K-supplying capacity of illite-dominated alluvial soils of the IGP is relatively high (Dobermann et al., 1996), long-term intensive cropping with inadequate application of K can result in K mining leading to large negative balances and depletion of native K reserves (Gami et al., 2001; Regmi et al., 2002; Singh et al., 2002; Bijay-Singh et al., 2003; Yadvinder-Singh et al., 2005). The K extraction is especially large in the RWS because straw is often removed from the field along with grain. Adequate input of K is essential to prevent further depletion of soil K.

Table 7. Change in soil K during one cycle of rice–wheat cropping due to application of K in a rice–wheat rotation at five locations in northern India. The K × M × location interaction was not significant at $P \le 0.05$ for all the listed parameters.

Parameter	Fatehgarh Sahib	Meerut	Banda	Barabanki	Bhagalpur
Change in exchangeable K, mg kg^{-1}					
No K	–6	–6	–7	–8	–9
+K	6	7	7	8	9
Difference†	13***	13***	14***	17***	18***
Change in non-exchangeable K, mg kg^{-1}					
No K	–30	–22	–19	–26	–18
+K	11	9	7	14	14
Difference	41***	31***	26***	40***	33**

** = Significant at $P \le 0.01$.

*** = Significant at $P \le 0.001$.

† Difference between non-rounded means for two no K treatments (no application of K, S, or Zn and application of S + Zn) and two +K treatments (application of K only and application of K with S + Zn).

Relationship between Soil Potassium and Crop Performance

Initial exchangeable soil K before the rice crop ranged from 60 to 162 mg kg^{-1} (0.15–0.42 cmol$_c$ kg^{-1}) across the 60 farmer's fields. An increase in rice and wheat yields from applied K was observed across the full range of exchangeable K (Fig. 2). The reported increase in yield was determined only from plots receiving S + Zn to ensure yields were not affected by deficiencies of these nutrients. Exchangeable K varied widely within each location. Yield gain for rice from applied K tended to decrease with increasing exchangeable K at Fatehgarh Sahib; but yield gain from applied K for both rice and wheat was obtained across locations in fields with relatively high soil K status as indicated by exchangeable K above 125 mg kg^{-1} (Fig. 2).

Initial non-exchangeable soil K before the rice crop ranged from 1228 to 3145 mg kg^{-1} across the 60 farmer's fields. Except at Fatehgarh Sahib where yield gain from applied K varied widely for rice and was small for wheat, the yield gain from applied K was relatively constant for rice and wheat across the range of non-exchangeable K across locations (Fig. 2).

The relatively consistent yield gain from applied K for rice and wheat across the range from 60 to 162 mg kg^{-1}, except for farms at Fatehgarh Sahib, raises concerns about the capability of soil testing based on an assessment of exchangeable soil K to detect the probable crop response to applied K for RWC in northern India (Fig. 2). Non-exchangeable soil K might be particularly important in the illite dominated soils of the IGP, and release and plant uptake of K from this soil fraction might

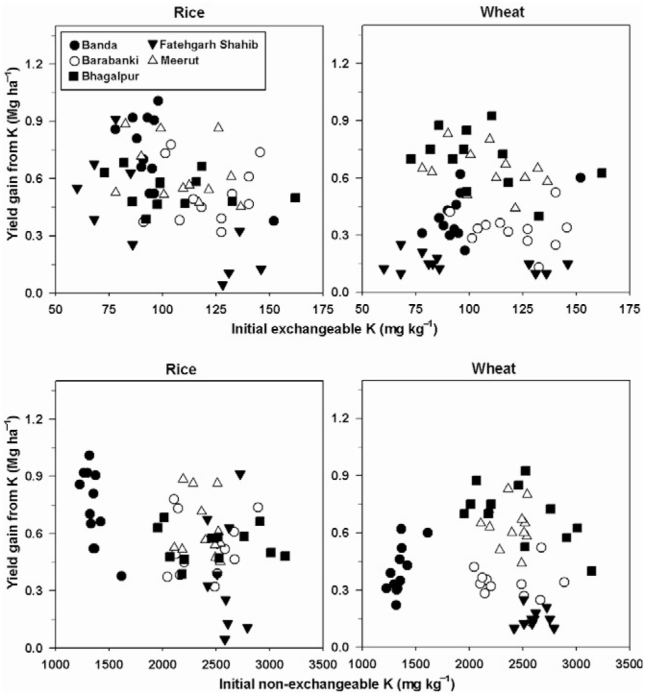

Fig. 2. Relationships of exchangeable K and non-exchangeable K with yield gain for rice and wheat from applied K across five locations with applied S and Zn in northern India.

Table 8. Reciprocal internal efficiencies (RIE) for N, P, and K for rice and wheat, expressed as nutrient in aboveground plant dry matter at maturity at five locations in northern India.†

	RIE				
Parameter	**Mean**	**SD‡**	**25% quartile**	**Median**	**75% quartile**
	kg nutrient Mg grain^{-1}				
Plant N					
Rice	19.4	0.87	18.9	19.4	19.8
Wheat	18.0	1.09	17.1	17.9	18.8
Plant P					
Rice	2.7	0.38	2.4	2.6	2.9
Wheat	3.5	0.33	3.3	3.6	3.7
Plant K					
Rice	20.8	1.58	19.7	20.8	21.8
Wheat	21.1	1.89	19.6	20.7	22.5

† Harvest index ranged from 0.40 to 0.49 for rice and from 0.37 to 0.46 for wheat. Number of observations = 240.

‡ SD = standard deviation.

Table 9. Effect of K applied to rice and wheat on reciprocal internal efficiency (RIE) of N, P, and K for rice and wheat, expressed as nutrient in aboveground plant dry matter at maturity across five locations in northern India.

		RIE		
Crop	**Nutrient**	**–K**	**+K**	**Difference**
		kg nutrient Mg grain^{-1}		
Rice	plant N	19.5	19.3	−0.27**
Rice	plant P	2.7	2.7	0.02ns†
Rice	plant K	19.9	21.6	1.64***
Wheat	plant N	17.9	18.0	0.08ns
Wheat	plant P	3.5	3.5	0.04ns
Wheat	plant K	20.2	22.0	1.86***

** Significant at $P \leq 0.01$.

*** Significant at $P \leq 0.001$.

† ns, not significant at $P \leq 0.05$.

mask the supply of K from the exchangeable K fraction (Bijay-Singh et al., 2003). Our findings, however, did not provide evidence that yield gain from applied K across a range of contrasting locations could be better predicted from non-exchangeable soil K than exchangeable soil K.

Nutrient Use Efficiency

Mean RIE for rice expressed as kilogram plant nutrient per megagram grain was 19.4 for N and 20.8 for K (Table 8), which is higher than the means for N (15.9) and K (17.7) reported by Buresh et al. (2010) for a large set of experiments across Asia. Mean RIE for P (2.7) was slightly lower than the mean (3.2) reported by Buresh et al. (2010). These differences with previously reported RIE do not appear to result from differences in HI. The HI for rice in our study ranged between 0.40 and 0.49, and the HI for rice in the study reported by Buresh et al. (2010) was $\geq$0.40.

The relatively high RIE for N in rice in our study might reflect the relatively high use of N fertilizer by farmers (Table 1). Mean RIE for K remained high even without added K (19.9) (Table 9). The corresponding mean reported by Buresh et al. (2010) for 462 observations without added K across Asia was 14.8. The relatively high RIE for K in our study suggests luxuriant uptake of K by rice in the farmer's fields. Soils had intermediate K fertility (Table 1), even through rice responded to applied K.

Mean RIE for wheat expressed as kilogram plant nutrient per megagram grain was 18.0 for N, 3.5 for P, and 21.1 for K (Table 8). Maiti et al. (2006) by comparison reported mean RIE of 15.8 for N, 3.2 for P, and 28.4 for K across five locations in northern India. The relatively high RIE for N in our study might reflect the relatively high use of N fertilizer on wheat (Table 1). Addition of K increased RIE for K (Table 9), but the increase in RIE for wheat was not to the level of the mean RIE for K (28.4) reported by Maiti et al. (2006). Such high RIE for K might reflect luxuriant uptake of K or relatively low HI. The HI for wheat in our study ranged from 0.37 to 0.46 across the 60 farmer's fields.

The use of a crop-specific RIE is an integral part of the site-specific nutrient management (SSNM) approach for calculating field-specific fertilizer K and P requirements (Buresh et al., 2010). Our study is rather unique in reporting RIE for both rice and wheat in the same farmer's fields across a range of locations. The RIEs for N and K averaged across all fields and treatments were near comparable for rice and wheat, but mean RIE for P was higher for wheat (3.5) than rice (2.7) (Table 8). Our results indicate RIE for K should be near comparable for rice and wheat but the RIE for P should be higher for wheat than for rice when using an SSNM-based calculation of fertilizer requirements for a rice–wheat rotation.

CONCLUSIONS

Previous reports on crop responses to K, S, and Zn in the RWS of the IGP, which are associated with nutrient mining and imbalanced application of fertilizer, have largely been confined to on-station and research-managed trials. Ours is one of the few multi-location trials with farmer's crop management in farmer's fields across the IGP.

Widespread deficiencies of K, S, and Zn in the soils of the IGP owing to unbalanced and inadequate application of these nutrients have become major constraints for high productivity of the RWS. The results of our on-farm experiments distributed across contrasting locations and fields established the importance of improved fertilizer management, which includes sufficient use of K, S, and Zn with judicious use of N and P to match crop needs. Our study clearly shows that use of K alone and with S + Zn can increase crop yields and productivity of the RWS, as indicated by the SREY (Table 3) and provide attractive net benefits to farmers. Inclusion of Zn improved grain Zn content in rice and wheat, which is critical for nutritional security in the region.

In our study rice and wheat at each of the five locations responded to applied K in one or more farms with relatively high soil K status of exchangeable K > 125 mg kg^{-1} (Fig. 2). This highlights the need for tools to reliably predict the need for fertilizer K at farms with relatively high soil K status. The SSNM-based approach as reported by Buresh et al. (2010) enables determination of field-specific fertilizer K and P requirements using nutrient balances, which consider the sustainable supply of K from soil reserves. Such an approach uses crop-specific RIE. The relative difference in RIE for K and P between rice and wheat, as reported in our study, provide valuable information for the development of computer-based decision tools capable of determining optimal nutrient requirements for each crop in the rice–wheat rotation.

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REFERENCES

Bijay-Singh, Yadvinder-Singh, P. Imas, and J.C. Xie. 2003. Potassium nutrition of the rice-wheat cropping system. Adv. Agron. 81:203–259. doi:10.1016/S0065-2113(03)81005-2

Buresh, R.J., M.F. Pampolino, and C. Witt. 2010. Field-specific potassium and phosphorus balances and fertilizer requirement for irrigated rice-based cropping systems. Plant Soil 335:35–64. doi:10.1007/s11104-010-0441-z

Chesnin, L., and C.H. Yien. 1951. Turbidimetric determination of available sulphates. Soil Sci. Soc. Am. Proc. 15:149–151. doi:10.2136/sssaj1951.036159950015000C0032x

Dobermann, A., K.G. Cassman, P.C. Sta. Cruz, M.A. Adviento, and M.F. Pampolino. 1996. Fertilizer inputs, nutrient balance, and soil nutrient-supplying power in intensive, irrigated rice ecosystems. II. Effective soil K supplying capacity. Nutr. Cycling Agroecosyst. 46:11–21. doi:10.1007/BF00210220

Dwivedi, B.S., V.K. Singh, and V. Kumar. 2011. Maximizing the rice-wheat system productivity through balanced fertilizer use under Typic Ustochrept soils of western Indo-Gangetic Plain. J. Farming Systems Res. Dev. 17:1–14.

FAI. 2011: Fertiliser statistics (2010–11). Fertiliser Assoc. of India, New Delhi.

Gami, S.K., J.K. Ladha, H. Pathak, M.P. Shah, E. Pasuquin, S.P. Pandey et al. 2001. Long-term changes in yield and soil fertility in a 20-year rice-wheat experiment in Nepal. Biol. Fertil. Soils 34:73–78. doi:10.1007/s003740100377

Hegde, D.M., and B.S. Dwivedi. 1992. Nutrient management in rice-wheat cropping system in India. Fert. News. 37(2):27–41.

Helmke, P.A., and D.L. Sparks. 1996. Lithium, sodium, potassium, rubidium, and cesium. In: D.L. Sparks et al., editors, Methods of soil analysis. Part 3. Chemical methods. SSSA Book Series no. 5. SSSA, Madison, WI. p. 551–574.

Ladha, J.K., H. Pathak, A. Tirol-Padre, and D. Dawe. 2003. Productivity trends in intensive rice–wheat cropping systems in Asia. In: J.K. Ladha et al., editors, Improving the productivity and sustainability of rice–wheat systems: Issues and impacts. ASA Spec. Publ. 65. ASA, CSSA, and SSSA, Madison, WI. p. 45–76.

Ladha, J.K., Yadvinder-Singh, O. Erenstein, and B. Hardy, editors.2009. Integrated crop and resource management in the rice–wheat system of South Asia. Int. Rice Res. Inst., Los Baños, Philippines.

Lindsay, W.L., and W.A. Norvell. 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci. Soc. Am. J. 42:421–428. doi:10.2136/sssaj1978.03615995004200030009x

Littell, R.C., G.A. Milliken, W.W. Stroup, R.D. Wolfinger, and O. Schabenberger. 2006. SAS for mixed models. SAS Inst., Cary, NC.

Maiti, D., D.K. Das, and H. Pathak. 2006. Simulation of fertilizer requirements for irrigated wheat in eastern India using QUEFTS model. Arch. Agron. Soil Sci. 52:403–418. doi:10.1080/03650340600768706

Olsen, S.R., C.V. Cole, F.S. Watanabe, and L.A. Dean. 1954. Estimation of available phosphorus in soils by extraction with sodium bicarbonate. USDA Circ. 939. USDA, Washington, DC.

Piper, C.S. 1966. Soil and plant analysis. Univ. of Adelaide Press, Adelaide, Australia.

Prasad, R. 2006. Zinc in soils and in plant, human and animal nutrition. Indian J. Fert. 2(9):103–119.

Regmi, A.P., J.K. Ladha, E. Pasuquin, H. Pathak, P.R. Hobbs, L.L. Shrestha et al. 2002. The role of potassium in sustaining yields in a long-term rice–wheat experiment in the Indo-Gangetic Plains of Nepal. Biol. Fertil. Soils 36:240–247. doi:10.1007/s00374-002-0525-x

SAS Institute. 2003. SAS Version 9.1. SAS Inst., Cary, NC.

SAS Institute. 2010. SAS Version 9.2. SAS Inst., Cary, NC.

Sharma, S.K. 2003. Characterization and mapping of rice–wheat system: Its changes and constraints to system sustainability. Final Report for National Agricultural Technology Project, Irrigated Agro-Ecosystem Production Systems Research (PSR 4.1). Project Directorate for Cropping Systems Res., Modipuram, Meerut, India.

Shivay, Y.S., D. Kumar, R. Prasad, and I.P.S. Ahlawat. 2008. Relative yield and zinc uptake by rice from zinc sulphate and zinc oxide coatings onto urea. Nutr. Cycling Agroecosyst. 80:181–188. doi:10.1007/s10705-007-9131-5

Shukla, A.K., and S.K. Behra. 2011. Zinc management in Indian agriculture. Indian J. Fert. 7(10):14–33.

Shukla, A.K., B.S. Dwivedi, V.K. Singh, and M.S. Gill. 2009. Macro role of micronutrients. Indian J. Fert. 5(5):11–30.

Singh, M., V.P. Singh, and D.D. Reddy. 2002. Potassium balance and release kinetics under continuous rice-wheat cropping system in Vertisol. Field Crops Res. 77:81–91. doi:10.1016/S0378-4290(01)00206-4

Singh, V.K., B.S. Dwivedi, A.K. Shukla, Y.S. Chauhan, and R.L. Yadav. 2005. Diversification of rice with pigeonpea in a rice-wheat cropping system on a Typic Ustochrept: Effect on soil fertility, yield and nutrient use efficiency. Field Crops Res. 92:85–105. doi:10.1016/j.fcr.2004.09.011

Singh, V.K., R. Tiwari, M.S. Gill, S.K. Sharma, K.N. Tiwari, B.S. Dwivedi, A.K. Shukla, and P.P. Mishra. 2008. Economic viability of site-specific nutrient management in rice-wheat cropping. Better Crops-India 2(1):16–19.

Subbiah, B.V., and G.L. Asija. 1956. A rapid procedure for the determination of available nitrogen in soils. Curr. Sci. 25:259–260.

Tandon, H.L.S. 2011. Sulphur in soils, crops and fertilizers. Fertilizer Development and Consultation Organization, New Delhi, India.

Tiwari, K.N., B.S. Dwivedi, and A. Subba Rao. 1992. Potassium management in rice-wheat system. In: R.K. Pandey et al., editors, Rice–Wheat Cropping System: Proceedings of the Rice–Wheat Workshop, Modipuram, Meerut. 15–16 Oct.1990. Project Directorate for Cropping Systems Res., Modipuram, Meerut, India. p. 93–114.

Williams, C.H., and A. Steinbergs. 1959. Soil sulphur fractions as chemical indices of available sulphur in some Australian soils. Aust. J. Agric. Res. 10:340–352. doi:10.1071/AR9590340

Yadvinder-Singh and Bijay-Singh. 2001. Efficient management of primary nutrients in the rice–wheat system. J. Crop Prod. 4:23–85. doi:10.1300/J144v04n01_02

Yadvinder-Singh, Bijay-Singh, and J. Timsina. 2005. Crop residue management for nutrient cycling and improving soil productivity in rice-based cropping systems in the tropics. Adv. Agron. 85:269–407. doi:10.1016/S0065-2113(04)85006-5