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Field-specific potassium and phosphorus balances and fertilizer requirements for irrigated rice-based cropping systems

Roland J Buresh • Mirasol F Pampolino • Christian Witt

Abstract Fertilizer K and P requirements for rice (*Oryza sativa* L.) can be determined with site-specific nutrient management (SSNM) using estimated target yield, nutrient balances, and yield gains from added nutrient. We used the QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) model with >8000 plot-level observations to estimate the relationship between grain yield and nutrient accumulation in above-ground dry matter of irrigated rice with harvest index $\geqslant 0.4$. Predicted reciprocal internal efficiencies (RIEs) at 60% to 70% of yield potential corresponded to plant accumulation of 14.6 kg N, 2.7 kg P, and 15.9 kg K per tonne of grain yield. These RIEs enable determination of plant requirements for K and P and net output of K and P in harvested grain and removed crop residues at a target yield. Yield gains for nutrient applied to irrigated rice averaged 12% for K and 9% for P for 525 to 531 observations. For fields without certain yield gain, fertilizer K and P requirements can be determined by a partial maintenance approach (i.e., fertilizer input < output in nutrient balance), which considers nutrient supply mediated through soil processes and balances trade-offs between financial loss with full maintenance rates and risk of excessive nutrient depletion without nutrient application. When yield gains to an added nutrient are certain, partial maintenance plus yield gain can be used to determine fertilizer requirements. The SSNM-based approach and algorithms enable rapid development of field-specific K and P management.

Keywords Field-specific nutrient management • nutrient balance • SSNM • rice • wheat • maize

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Abbreviations *CRR; crop residue retained: FK; fertilizer K: FM; fraction of full maintenance: FP; fertilizer P: GY; grain yield: HI; harvest index: IE; internal efficiency: IGP; Indo-Gangetic Plains: QUEFTS; Quantitative Evaluation of the Fertility of Tropical Soils: RE; recovery efficiency: RIE; reciprocal internal efficiency: RTDP; Reversing Trends in Declining Productivity: SSNM; site-specific nutrient management*

Introduction

Rice (*Oryza sativa* L.) is the main staple food crop in Asia, which accounts for about 90% of global rice production. Irrigated rice covers half the rice-growing area and accounts for about 75% of total rice production (Maclean et al. 2002). Continuous rice cultivation with two and occasionally three crops per year is common in tropical Asia. Rice in rotation with other crops, particularly wheat (*Triticum aestivum* L.), is common in subtropical Asia (Ladha et al. 2009), and the rotation of maize (*Zea mays* L.) with irrigated rice is increasing in importance in Asia (Ali et al. 2008). Fertilizer use has contributed to increasing production of rice-based systems since the Green Revolution, and the effective use of supplemental nutrients remains vital for essential increases in the production of rice and associated cereal staples to meet rising demand for food security and political stability.

Plots of land for cultivation of rice-based cropping systems in Asia are typically small and spatially variable in management. Large variations in nutrient balances and nutrient requirements can exist across small distances within a landscape due to differences in retention of crop residues, historical fertilizer use, input of organic materials, inherent soil fertility, and crop yield attainable with farmers' management practices. Existing blanket fertilizer recommendations for large areas or agro-ecological zones fail to account for these variations in crop needs for supplemental nutrients among fields within small distances. Approaches and algorithms for tailoring fertilizer requirements to field-specific needs of crops are necessary to further improve productivity and profitability from fertilizer use.

Algorithms for determining fertilizer recommendations are often derived from factorial fertilizer trials conducted across multiple locations. Site-specific nutrient management (SSNM) for rice arose in the mid-1990s as an alternative approach for dynamic management of nutrients to optimize supply and demand of a nutrient within a specific field in a particular cropping season (Dobermann et al. 2004). The SSNM approach reasoned that fertilizer requirements should be based on more generic relationships such as internal nutrient efficiency, which is the amount of grain yield produced per unit of nutrient accumulated in above-ground plant dry matter (Witt et al. 1999). The QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) model developed by Janssen et al. (1990) was used to provide a generic empirical relationship between grain yield and nutrient accumulation in rice plants (Witt et al. 1999), which was subsequently combined with the estimation of attainable yield, nutrient balances, and probable yield gains from added nutrient to determine field-specific fertilizer requirements for rice (Witt and Dobermann 2004).

The determination of field-specific fertilizer N requirements in the SSNM approach for rice has subsequently been modified to use a target agronomic efficiency of fertilizer N use, which is the increase in yield per unit of fertilizer N applied, and an estimated field-specific yield gain to applied N (Buresh and Witt 2007; Witt et al. 2007). The determination of fertilizer K and P requirements in the SSNM approach, on the other hand, has continued to use internal nutrient efficiency combined with estimates of attainable yield, nutrient balances, and probable yield gains from added nutrient within specific fields (Witt et al. 2007). The SSNM approach has recently been applied to wheat (Khurana et al. 2008) and maize (Witt et al. 2009).

Witt et al. (2007) advocated use of nutrient balances with full maintenance of soil fertility, in which the applications of fertilizer K and P are sufficient to match the output of the nutrients. Such an approach does not adjust fertilizer K and P rates for enhanced availability of nutrients through soil biological, chemical, and physical processes. Moreover, the application of fertilizer at full maintenance can result in financial loss when the crop does not respond to the added nutrient. An increase in farm-gate fertilizer prices relative to the farm-gate price of produce further increases this financial loss. Failure to apply K or P, on the other hand, can result in nutrient depletion and eventual loss in yield, which could take a number of seasons before detection (Abdulrachman et al. 2006). The importance of soil biological, chemical, and physical processes on nutrient availability and the dramatic fluctuations in fertilizer prices highlight the need to re-examine full maintenance approaches for determining fertilizer K and P requirements. Algorithms are needed for determining fertilizer K and P rates that effectively consider soil processes and soil characteristics mediating K and P availability and balance the trade-offs between profitability in the short term and sustainable productivity in the longer term.

Technological approaches and algorithms for developing fertilizer requirements tailored to field-specific needs of crops in irrigated rice-based cropping systems must be based on robust scientific principles applicable across the field-level variability and diversity of crop-growing conditions. At the same time, approaches must be relatively simple with minimal characterization or interviewing of farmers for each field in order to ensure rapid, cost-effective delivery of field-specific guidelines to millions of small-scale farmers. Technological approaches and algorithms should strive to draw upon existing research information in order to avoid delays in reaching farmers with practical solutions based on scientific principles.

Nutrient balances and fertilizer requirements determined with SSNM for irrigated rice rely on reciprocal internal efficiency (RIE), which is the amount of the nutrient in above-ground plant dry matter per tonne of grain production. Values currently used with SSNM for irrigated rice were derived with the QUEFTS model by Witt et al. (1999). Given the importance of RIE in determining fertilizer requirements, there is merit after a decade to re-examine with a larger data set the robustness of RIEs used for irrigated rice.

The objectives of this study are:

1) To determine, using a large data set for irrigated rice from across Asia, the relationship between rice grain yield and N, P, and K accumulation in total above-ground plant dry matter of mature rice, and through this to confirm RIE values for K and P for use in determining fertilizer requirements for semi-dwarf irrigated rice;
2) To assess at the field level through K and P nutrient balances the factors, uncertainties, and emerging trends affecting the determination of field-specific fertilizer K and P requirements for rice–rice, rice–wheat, and rice–maize cropping systems; and
3) To examine and compare revised approaches for calculating field-specific K and P fertilizer rates that can consider the net effect of soil processes and soil characteristics mediating K and P availability and balance the trade-offs between short-term profitability of fertilizer use and longer term sustainability of the productivity of high-yielding rice-based systems.

We provide alternatives to factorial field trials and rigid nutrient balances for determining fertilizer K and P requirements. The framework we present does not specifically consider soil–plant–nutrient interactions and biological processes mediating nutrient availability.

Materials and methods

Internal nutrient efficiencies for rice

The QUEFTS model (Janssen et al. 1990) as modified and described by Witt et al. (1999) was used with a large data set to develop relationships between grain yield and nutrient accumulation in total above-ground plant dry matter of rice at maturity. The data originated from irrigated rice production areas in seven countries across tropical and subtropical environments in Asia (Table 1). Data for rice grain yield, harvest index, and plant accumulation of N, P, and K were compiled from various research projects and then grouped into separate data sets for N, P, and K. The data set for each nutrient contained results from all plots with measurements for both plant accumulation of the nutrient and grain yield (Table 1).

Table 1 Origin of data used to examine the relationship between rice grain yield and accumulation of N, P, and K in total above-ground dry matter at maturity

Country	Type of experiment	Years	Number of plot-level observations (n)					
			HI[a] = 0.4 to 0.63			HI = 0.2 to 0.4		
			N	P	K	N	P	K
Bangladesh	On-farm nutrient omission trials	2000-2002	153	100	99	29	16	17
	On-farm fertilizer trials	2000-2002	259	325	325	98	98	98
China	On-farm nutrient omission trials	2001-2002	38	38	38			
	On-farm fertilizer trials	1998-2002	415	415	415			
India	On-farm nutrient omission trials	2001-2004	939	936	939	3	3	3
	On-farm fertilizer trials	1997-2004	2086	2086	2086			
Indonesia	On-farm nutrient omission trials	2001-2002	110	72	72			
	On-farm fertilizer trials	1997-2002	602	602	599	10	10	10
	On-station experiments	2001-2003	144	144	144			
Philippines	On-farm nutrient omission trials	2001-2002	36	36	36	5	5	5
	On-farm fertilizer trials	1997-2002	616	616	616	110	110	110
	On-station experiments	1991-2007	8279	1781	1783	409	163	163
Thailand	On-farm fertilizer trials	1997-2000	206	206	206	80	80	80
Vietnam	On-farm nutrient omission trials	2002-2003	150	150	150	10	10	10
	On-farm fertilizer trials	1997-2003	1474	1441	1475	68	62	68
Total			15507	8948	8983	822	557	564

[a] HI = harvest index

In each of the seven countries, except Thailand, data originated from both nutrient omission trials and fertilizer evaluation trials conducted in farmers' fields. Data from Bangladesh originated from research described by Alam et al. (2005). Data from on-farm trials before 2001 in other countries originated from the Reversing Trends in Declining Productivity project (Dobermann et al. 2002). On-farm data from 2001 onward originated from the subsequent Reaching Toward Optimal Productivity project in which SSNM was further refined into guidelines for rice fertilization (Witt et al. 2007). Data from on-station experiments in the Philippines originated from several long-term experiments that included treatments without application of N, P, or K but ample application of other nutrients to meet crop needs. All data were for irrigated rice, and water rarely limited plant growth. In all cases semi-dwarf, modern high-yielding indica cultivars were grown with good agronomic practices. Comparable methodologies for plant sampling, yield determination, and analysis for plant nutrients were used for collected data across the countries and experiments (Witt et al. 1999).

Internal nutrient efficiency (IE) is defined as the amount of grain yield in kg ha^{-1} (adjusted to 0.14 g water g^{-1} fresh weight) produced per kg of plant N, P, or K accumulation in above-ground plant dry matter expressed on an oven dry basis. Reciprocal internal efficiency (RIE) is the amount of N, P, or K in the above-ground plant dry matter per 1000 kg of grain production. Harvest index is grain yield expressed as a proportion of total above-ground plant dry matter (kg grain per kg total above-ground dry matter).

Relationships between grain yield and plant nutrient accumulation as predicted by QUEFTS follow a linear-parabolic-plateau model, which depends on an established maximum yield potential and coefficients of maximum nutrient accumulation (a) and maximum nutrient dilution (d). The a and d coefficients used in this paper were the 2.5th and 97.5th percentile of the measured IE (Witt et al. 1999). The predicted model is linear up to about 60% to 70% of the yield potential, which is seldom exceeded in farmers' fields. Internal nutrient efficiencies determined from the linear portion of the model represent the amount of nutrient needed to achieve a grain yield for modern high-yielding rice cultivars across a wide range of yields attainable in farmers' fields (Witt et al. 1999).

The RIEs obtained for a data set with the QUEFTS model are intended for use in calculating nutrient balances and fertilizer rates for modern high-yielding rice cultivars (Witt and Dobermann 2004) grown in farmers' fields with good agronomic practices and balanced use of N, P, and K fertilizers. We therefore excluded from analysis with QUEFTS the data from plots either with suspected yield loss due to pests and disease or known to have unbalanced application of fertilizer.

Harvest index for the entire data set ranged from 0.2 to 0.63. Low harvest indices suggest that disease, weeds, or insect pests resulted in some yield loss. Like Witt et al. (1999) and Haefele et al. (2003), we excluded data with harvest index <0.4 from the determination of relationships and internal nutrient efficiencies with QUEFTS for semi-dwarf irrigated rice. About 5% of the observations in the entire data set had harvest index <0.4 (Table 1).

Mean and median RIE for N, P, and K are consistently lower for rice grown without addition of the nutrient (nutrient omission plots) than with full fertilization due to dilution of the nutrient in plants not fertilized with the nutrient (Table 2). We therefore excluded all nutrient omission plot data from the analysis with QUEFTS. Data from NPK fertilized plots with harvest index from 0.4 to 0.63 as summarized in Table 2 were used to develop relationships and determine RIE with QUEFTS.

Determination of K and P balances

Simple nutrient balances for K and P in the absence of fertilizer input were determined for a single rice crop, one rice–wheat cropping cycle, and one rice–maize cropping cycle. The balances took into account the fraction of retained crop residue and the inputs of nutrient from irrigation water and added organic materials.

K balance for rice = $K_W + K_{OM} + K_{CRr} - K_L - (GY_r \times RIE_{Kr})$ [1]

Table 2 Reciprocal internal efficiency (RIE) for N, P, and K at maturity of irrigated rice as affected by location and treatment. Results are for the data set with harvest index (HI) = 0.4 to 0.63 as described in Table 1

Parameter	n[a]	RIE (kg nutrient in above-ground dry matter per 1000 kg grain)				
		Mean	SD[b]	25% quartile	Median	75% quartile
Plant N						
Full fertilized plots	13327	16.4	3.2	14.2	16.2	18.3
- N plots	2180	12.8	2.6	11.2	12.6	14.2
All data	15507	15.9	3.3	13.5	15.7	17.9
Plant P						
Full fertilized plots	8404	3.2	0.8	2.7	3.2	3.7
- P plots	544	2.6	0.7	2.1	2.6	3.0
All data	8948	3.2	0.8	2.7	3.2	3.6
Plant K						
Full fertilized plots	8521	17.8	4.6	14.2	17.2	20.8
- K plots	462	14.8	5.5	11.0	12.4	18.4
All data	8983	17.7	4.7	14.0	17.0	20.7

[a] n = number of observations [b] SD = Standard Deviation

K balance for rice–wheat or rice–maize = $K_W + K_{OM} + K_{CRr} + K_{CRwm} - K_L - (GY_r \times RIE_{Kr}) - (GY_{wm} \times RIE_{Kwm})$ [2]

P balance for rice = $P_{OM} + P_{CRr} - (GY_r \times RIE_{Pr})$ [3]

P balance for rice–wheat or rice–maize = $P_{OM} + P_{CRr} + P_{CRwm} - (GY_r \times RIE_{Pr}) - (GY_{wm} \times RIE_{Pwm})$ [4]

where K and P balances and each input are expressed in kg ha^{-1}, K_W is K input with irrigation water for an entire cropping cycle, K_{OM} and P_{OM} are K and P inputs from added organic materials, K_{CRr} and P_{CRr} are K and P inputs with retained residues of rice, K_{CRwm} and P_{CRwm} are K and P inputs with retained residues of wheat or maize, K_L is K loss by percolation or leaching in kg ha^{-1}, GY_r and GY_{wm} are targeted grain yields in t ha^{-1} for rice and wheat or maize, RIE_{Kr} and RIE_{Pr} are reciprocal internal efficiencies of rice for K and P, and RIE_{Kwm} and RIE_{Pwm} are reciprocal internal efficiencies of wheat or maize for K and P. Input of P in irrigation water, loss of P by percolation and leaching, and inputs of P and K with rainfall are treated as negligible and not included in the equations (Dobermann et al. 1998).

The P and K balances reported in this study used RIEs for rice determined from the linear portion of the QUEFTS model predicted in this study (Table 3). The RIEs used for wheat (21.6 kg plant K and 3.5 kg plant P per 1000 kg grain) were obtained from the linear portion of a predicted QUEFTS model using a data set with 1102 observations for K and 1119 observations for P compiled from across Asia (IPNI, unpublished data). Pathak et al. (2003), using a smaller data set from India, reported a higher RIE for K (28.5) and a comparable RIE for P (3.5), and Liu et al. (2006), using a data set from China, reported relatively comparable RIE for K (23.0) and P (3.7).

Table 3 Constants for internal efficiency (IE) corresponding to maximum accumulation (a) and maximum dilution (d) and reciprocal internal efficiency (RIE) calculated by QUEFTS for the linear portion of the relationship between rice grain yield and nutrient accumulation in total above-ground dry matter of rice at maturity

Nutrient	IE constants (kg grain/kg nutrient in above-ground dry matter)				RIE (kg nutrient in above-ground dry matter per 1000 kg grain)	
	Maximum accumulation (a)		Maximum dilution (d)			
	Witt et al. (1999)	This study	Witt et al. (1999)	This study	Witt et al. (1999)	This study
N	42	43	96	94	14.7	14.6
P	206	202	622	595	2.6	2.7
K	36	36	115	95	14.5	15.9

Data are from NPK fertilized plots with harvest index (HI) = 0.4 to 0.63 as described in Table 2. The grain yield potential was set to 10 t ha^{-1}. Constants a and d were calculated by excluding the upper and lower 2.5 percentiles (2.5th and 97.5th) of all IE data

The RIEs used for maize (17.4 kg plant K and 2.56 kg plant P per 1000 kg grain) were obtained at 80% of yield potential of a QUEFTS model predicted with yield potential = 14 t ha^{-1} using a data set with 2361 observations for K and 2363 observations for P compiled from Nebraska in the USA, Indonesia, and Vietnam (Setiyono et al. 2010). The RIEs were obtained at 80% of yield potential because this yield level is attainable with hybrid maize in farmers' fields in Southeast Asia. Liu et al. (2006), using a smaller data set from China, reported higher RIE for K (23.1) and P (4.3).

The K and P inputs from residues for a crop (K_{CR} and P_{CR}) depend upon amount and nutrient content of the above-ground crop biomass retained in the field after harvest.

$K_{CR} = GY \times RIE_K \times (1 - HI_K) \times CRR$ [5]

$P_{CR} = GY \times RIE_P \times (1 - HI_P) \times CRR$ [6]

where HI_K and HI_P are K and P harvest indices for a crop expressed as kg nutrient in grain per kg nutrient in total above-ground dry matter, and CRR for a crop is the fraction of total crop residue retained in the field after harvest.

The K and P nutrient balances reported in this study used K and P harvest indices (HI_K = 0.15 and HI_P = 0.7) for rice that were determined from NPK fertilized plots in this study (Table 4). Nutrient balances reported in this study with wheat and maize used HI_K = 0.2 for wheat and maize, HI_P = 0.6 for wheat, and HI_P = 0.85 for maize because they approximate values obtained from relatively large data sets from multiple locations. In a data set for wheat from Bangladesh and India with 305 observations for K and 323 observations for P, the median HI_K = 0.22 and the median HI_P = 0.60 (IPNI, unpublished data). In a data set for maize from Nebraska, Indonesia, and Vietnam with 2361 observations for K and 2363 observations for P, the median HI_K = 0.16 and the median HI_P = 0.86 (Setiyono et al. 2010).

Table 4 Nutrient harvest index (HI) for N, P, and K of irrigated rice obtained from NPK fertilized plots with HI = 0.4 to 0.63 as described in Table 2

Nutrient	n[a]	Nutrient HI (kg nutrient in grain per kg nutrient in total above-ground dry matter)				
		Mean	SD[b]	25% quartile	Median	75% quartile
N	13327	0.63	0.07	0.59	0.63	0.67
P	8404	0.69	0.10	0.62	0.69	0.77
K	8521	0.16	0.06	0.12	0.15	0.19

[a] n = number of observations

[b] SD = standard deviation

Determination of fertilizer K and P rates

The principles of QUEFTS can be used to determine fertilizer P and K requirements to achieve a targeted yield through approaches based on either expected yield gain from the added nutrient or estimated nutrient balance (Witt and Dobermann 2004). In the yield gain approach, the fertilizer K (FK) or fertilizer P (FP) (in kg ha^{-1}) required to achieve a targeted yield (GY, expressed in t ha^{-1}) is a function of the expected yield gain from the added nutrient, the RIE for the nutrient, and the use efficiency of the applied nutrient:

$FK = (GY - GY_{0K}) \times RIE_K/RE$ [7]

$FP = (GY - GY_{0P}) \times RIE_P/RE$ [8]

where GY_{0K} and GY_{0P} are grain yield in t ha^{-1} in the respective nutrient omission plot in which the nutrient of interest is not applied, RIE of a nutrient is determined with QUEFTS (Table 3), and use efficiency is the recovery efficiency of the applied nutrient (RE_K or RE_P) expressed in kg kg^{-1}. Because RIE is a constant to only 60% to 70% of yield potential, the targeted grain yield should not exceed about 70% of the yield potential when RIE is derived from the linear portion of the QUEFTS model. Current yields of irrigated rice in Asia are generally below 70% of yield potential (Dobermann et al. 2002).

Witt and Dobermann (2004), using a data set for irrigated rice from across Asia, observed RE_K ranging from 0.35 to 0.66 kg kg^{-1} and RE_P ranging from 0.22 to 0.35 kg kg^{-1} between the median and the 75% quartile. Using these values together with RIE reported in Witt et al. (1999), they estimated as a general rule that 25 kg K or 9 kg P are required to raise the respective nutrient-limited yield by 1 t ha^{-1}. The data set used by Witt and Dobermann (2004) did not include highly weathered soils (i.e., Oxisols and Ultisols) and volcanic soils (i.e., Andisols) with high capacity to fix P. P-fixing soils would likely have lower RE_P and corresponding higher fertilizer P requirements.

Expected yield gains from the addition of a nutrient ($GY - GY_0$) as obtained with the nutrient omission plot technique can be used to determine the need of a crop for fertilizer. We used results from 525 K omission plot trials and 531 P omission plot trials conducted in farmers' fields in Bangladesh, India, Indonesia, and Vietnam (Table 1) to estimate the gain in rice yield from K and P fertilization. The yield gain from application of K or P was determined from the difference in grain yield between a plot with full fertilization of N, P, and K at sufficiently high rates to avoid limitation of these nutrients and an adjacent plot without application of K or P (i.e., a nutrient omission plot) but with sufficient amounts of other nutrients to prevent their limitations on yield. The full-fertilized and nutrient omission plots in a given field were managed identically except for the omission of the nutrient of interest in plots without K or P. The difference in grain yield between the full-fertilized plot and the nutrient omission plot represents the expected yield gain from addition of the nutrient to overcome the deficit between the crop demand for the nutrient and indigenous supply of the nutrient from sources other than fertilizer.

Fertilizer K and P requirements to achieve a targeted yield can also be estimated with QUEFTS principles through nutrient input-output balances. Witt and Dobermann (2004) used the following equations based on nutrient balance to estimate fertilizer K (FK) or fertilizer P (FP) requirements (in kg ha^{-1}) for a crop with full maintenance of soil K and P.

$FK = (GY \text{ x } RIE_K) + ((GY - GY_{0K}) \text{ x } RIE_K) - K_{CR} - K_W - K_{OM} + K_L$ [9]

$FP = (GY \text{ x } RIE_P) + ((GY - GY_{0P}) \text{ x } RIE_P) - P_{CR} - P_{OM}$ [10]

where K_{CR} and P_{CR} are K and P inputs with retained residues, and other inputs and losses are as defined for equations 1 to 4. Inputs and losses are all expressed in kg ha^{-1}. Witt and Dobermann (2004) included the expected yield gain from addition of a nutrient ($GY - GY_0$) in the determination of fertilizer requirements to ensure that fertilizer K and P rates in the presence of a yield gain were increased by the amount of the nutrient uptake deficit to slowly build up soil nutrient supplies.

In our study we did not include yield gain in the estimation of fertilizer K and P based on a nutrient balance approach. We examined two options using nutrient balances to calculate fertilizer K and P rates based on partial maintenance with gradual drawdown or depletion of soil K and P rather than full maintenance of soil K and P. In one option with partial maintenance, fertilizer K and P requirements are calculated as a fraction of full maintenance (FM) as shown in equations 11 and 12.

FK with fractional K depletion $= (GY \text{ x } RIE_K - K_{CR} - K_W - K_{OM} + K_L) \text{ x} FM$ [11]

FP with fractional P depletion $= (GY \text{ x } RIE_P - P_{CR} - P_{OM}) \text{ x} FM$ [12]

The other option with partial maintenance allows drawdown of K or P from soil reserves up to a threshold limit (K_S or P_S in kg ha^{-1}), which is treated as an input in the nutrient balance.

FK with limited K depletion $= GY \text{ x } RIE_K - K_{CR} - K_W - K_{OM} - K_S +$ [13]

FP with limited P depletion $= GY \text{ x } RIE_P - P_{CR} - P_{OM} - P_S$ [14]

The FM, K_S, and P_S terms can be used to estimate the net effect of soil biological, chemical, and physical processes and soil characteristics on supply of soil K and P. When FM = 1 or when K_S or $P_S = 0$, the calculated fertilizer rates for a nutrient ensure full maintenance with no drawdown of the nutrient from soil reserves.

We also combined the partial maintenance and yield gain approaches for determining fertilizer K and P when crop response to the nutrient is certain.

FK with fractional K depletion $= ((GY \text{ x } RIE_K - K_{CR} - K_W - K_{OM} + K_L) \text{ x } FM) + ((GY - GY_{0K}) \text{ x } RIE_K/RE_K)$ [15]

FP with fractional P depletion $= ((GY \text{ x } RIE_P - P_{CR} - P_{OM}) \text{ x } FM) + ((GY - GY_{0P}) \text{ x } RIE_P/RE_P)$ [16]

FK with limited K depletion $= (GY \text{ x } RIE_K - K_{CR} - K_W - K_{OM} - K_S + K_L) + ((GY - GY_{0K}) \text{ x } RIE_K/RE_K)$ [17]

FP with limited P depletion $= (GY \text{ x } RIE_P - P_{CR} - P_{OM} - P_S) + ((GY - GY_{0P}) \text{ x } RIE_P/RE_P)$ [18]

Fertilizer K (FK) and P (FP) rates are set to zero whenever the value calculated in equations 11 through 18 is negative.

Results

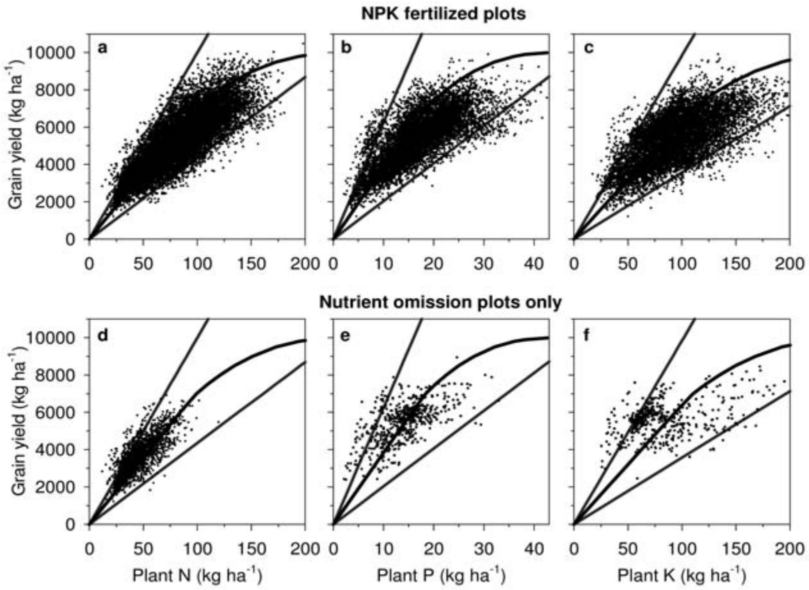
Internal nutrient efficiencies for rice

Relationships for grain yield with total plant N, P, and K developed with

QUEFTS using data from NPK fertilizer plots with harvest index = 0.4 to 0.63 (Table 2) are shown in Fig. 1abc. The yield potential (10 t ha^{-1}) and the limits for data exclusion (upper and lower 2.5 percentiles) used to determine the functions relating grain yield to the maximum accumulation (a) and dilution (d) of a nutrient are identical to those used by Witt et al. (1999) (Table 3). The IE at maximum accumulation (a) of a nutrient (Table 3) represents the slope of the lower boundary line in Fig. 1, whereas the IE at maximum dilution (d) of a nutrient (Table 3) represents the slope of the upper boundary line in Fig. 1.

Observations from nutrient omission plots are shown for no added N in Fig. 1d, no added P in Fig. 1e, and no added K in Fig. 1f. In each case the presented boundary lines and QUEFTS model were derived using data from NPK fertilized plots (Table 3). In the absence of a nutrient, many observations concentrated near the upper boundary line for IE, which generally reflects severe nutrient deficiency. High IE for a nutrient in plots where the nutrient is omitted (Fig. 1def) corresponds to markedly lower RIE for nutrient omission plots than for NPK fertilized plots (Table 2). For P and K about 5% of the total plot-level observations were from nutrient omission plots. In these cases, the inclusion of nutrient omission plots in the data set had no pronounced effect on the calculated RIE. For N, for which 14% of the total plot-level observations were from N omission plots, the inclusion of N omission plots in the data set reduced the calculated RIE by 3% (Table 2).

Fig. 1 Relationship between rice grain yield and accumulation of N, P, and K in total above-ground dry matter of rice at maturity, using data from NPK fertilizer plots (abc) and nutrient omission plots only (def) with harvest index = 0.4 to 0.63 as described in Table 2. Boundary lines and trend line for each nutrient in each graph are calculated by the QUEFTS model using data for the NPK fertilized plots described in Table 2 and based on exclusion of the upper and lower 2.5 percentiles of all internal nutrient efficiencies. The trend lines are with yield potential set at 10 t ha^{-1} as described by Witt et al. (1999)



The IEs for N, P, and K were relatively low at low harvest indices (Fig. 2). At harvest index = 0.2 to 0.4, many observations for the relationship of grain yield and plant N, P, or K were concentrated near the lower boundary line determined with QUEFTS using data from NPK fertilizer plots with harvest index = 0.4 to 0.63. Such low IE in the absence of biotic or abiotic stress would reflect excess or luxuriant plant uptake of a nutrient. In this study with semi-dwarf, modern high-yielding rice cultivars, the low harvest indices probably arose from loss in grain yield relative to dry matter production due to non-nutrient constraints such as disease, insect pests, or water deficit. As harvest index increased, the observations increasingly concentrated nearer to the QUEFTS-derived relationship for grain yield and plant nutrient accumulation (Fig. 2).

The RIEs for N, P, and K increased with decreasing harvest index (Table 5). The effect of harvest index on RIE was most pronounced for K and least pronounced for P, reflecting the relatively high proportion of plant K and low portion of plant P that accumulates in crop residue rather than grain. The reliable determination of nutrient balances that include nutrient inputs from crop residues is consequently relatively more reliant on a robust RIE value for K than for P (see equations 5 and 6).

The RIE estimated as the mean or median of the data set for NPK fertilizer plots (Table 2) was larger than the RIE derived from the linear portion of the QUEFTS model (Table 3). QUEFTS predicted the balanced nutrient accumulation of 14.6 kg N, 2.7 kg P and 15.9 kg K per tonne of grain across a range of grain yields up to about 70% of the yield potential. The corresponding values obtained from means for the entire data set were 16.4 kg N, 3.2 kg P, and 17.8 kg K per tonne of grain (Table 2). The RIEs for nutrients are lower with QUEFTS because values derived with QUEFTS are from the slope for only the linear portion of the predicted relationship. This is confirmed by the increase in RIE predicted by QUEFTS as target yield increases above 60% to 70% of the yield potential (Table 6).

An objective of this study was to establish a confirmed robust RIE for N, P, and K for use in calculating nutrient balances and fertilizer rates for semi-dwarf, high-yielding irrigated rice cultivars grown in farmers' fields with good agronomic practices and balanced use of nutrient inputs. We therefore sought to

Fig. 2 Effect of harvest index on relationship between rice grain yield and accumulation of N, P, and K in total above-ground dry matter of rice at maturity, using the entire data set reported in Table 1. Boundary lines and trend line for each nutrient in each graph are calculated by the QUEFTS model using data for the NPK fertilized plots with harvest index = 0.4 to 0.63 as described in Table 2 and based on exclusion of the upper and lower 2.5 percentiles of all internal nutrient efficiencies. The trend lines are with yield potential set at 10 t ha^{-1} as described by Witt et al. (1999)

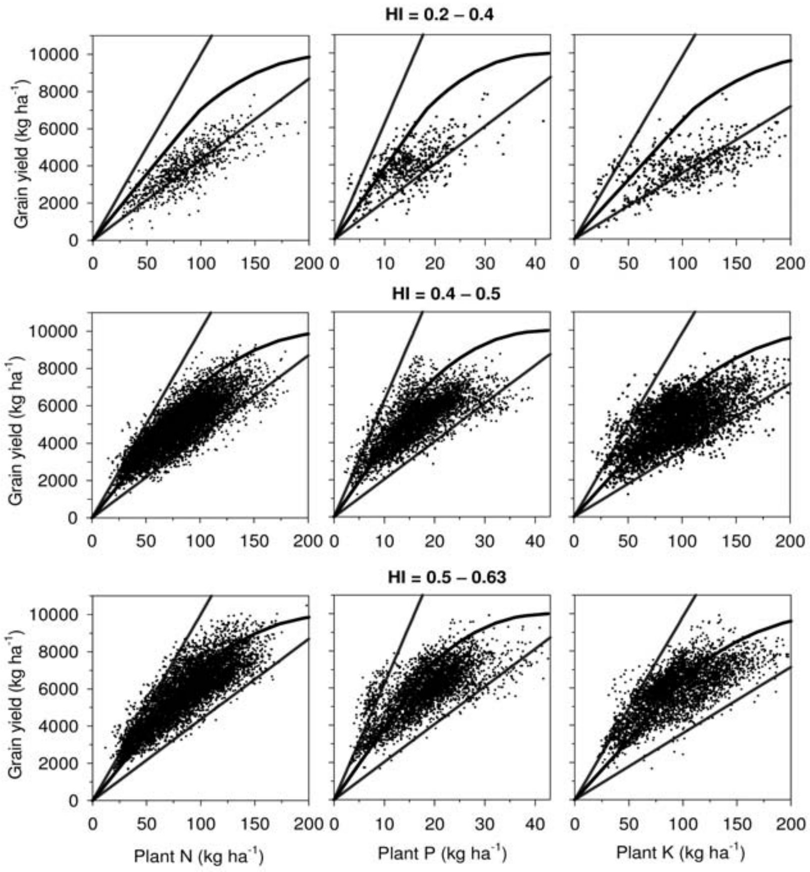


Table 5 Reciprocal internal efficiency (RIE) for N, P, and K at maturity of irrigated rice as affected by harvest index (HI). Results are for the data set described in Table 1

Parameter	n[a]	RIE (kg nutrient in above-ground dry matter per 1000 kg grain)				
		Mean	SD[b]	25% quartile	Median	75% quartile
Plant N						
HI: 0.2-0.4	822	23.0	5.9	19.5	22.2	25.4
HI: 0.4-0.5	8156	16.7	3.4	14.3	16.4	18.8
HI: 0.5-0.63	7351	14.9	3.0	12.7	15.0	16.9
Plant P						
HI: 0.2-0.4	557	3.9	1.2	3.0	3.7	4.5
HI: 0.4-0.5	4680	3.2	0.8	2.7	3.3	3.7
HI: 0.5-0.63	4268	3.1	0.8	2.6	3.1	3.6
Plant K						
HI: 0.2-0.4	564	27.3	8.1	23.0	27.6	32.3
HI: 0.4-0.5	4708	19.1	5.0	15.5	18.7	22.3
HI: 0.5-0.63	4275	16.1	3.8	13.2	15.4	18.6

[a] n = number of observations

[b] SD = standard deviation

Table 6 Reciprocal internal efficiency (RIE) calculated by QUEFTS to establish target grain yields

Grain yield (kg ha^{-1})	Percentage of yield potential (%)	RIE (kg nutrient in above-ground dry matter per 1000 kg grain)		
		N	P	K
5000	50	14.6	2.7	15.9
6000	60	14.6	2.7	15.9
7000	70	14.7	2.7	16.0
7500	75	15.0	2.7	16.3
8000	80	15.5	2.8	17.0
8500	85	16.2	3.0	17.7
9000	90	17.2	3.1	18.7

Data are from NPK fertilized plots with harvest index (HI) = 0.4 to 0.63 as described in Table 2. The grain yield potential was set to 10 t ha^{-1}

exclude from analysis with QUEFTS the data from plots where plant growth was limited by factors other than nutrient supply. The strong influence of harvest index on RIE, especially for K and N, verifies the merit of excluding data with harvest index <0.4 when factors other than nutrients were likely limiting the yield of semi-dwarf cultivars. The exclusion of data from omission plots slightly increased RIE obtained from the linear portion of the QUEFTS prediction. With the exclusion of omission plot data, the RIE for nutrients increased from 14.1 to 14.6 kg N per tonne of grain, 2.6 to 2.7 kg P per tonne of grain, and 15.6 to 15.9

kg K per tonne of grain (data not shown). This suggests that the exclusion of omission plot data in the QUEFTS analysis is merited because results from omission plots tend to concentrate at near the upper boundary line for maximum dilution (Fig. 1def).

The IEs for maximum accumulation (a) and dilution (d) and the RIEs obtained with QUEFTS in this study were comparable to values reported by Witt et al. (1999) using a smaller data set (Table 3). At harvest index of ⩾0.4, which is common for semi-dwarf, high-yielding rice, the RIE of 14.7 reported by Witt et al. (1999) remained essentially unchanged at 14.6 kg plant N per tonne of grain, and the RIE of 2.6 reported by Witt et al. (1999) remained essentially unchanged at 2.7 kg plant P per tonne of grain. The RIE for K increased slightly from 14.5 to 15.9 kg plant K per tonne of grain (Table 3). The close match between this study and Witt et al. (1999) confirms the robustness of the RIEs from Witt et al. (1999) that have been used for a decade to determine fertilizer K and P requirements within SSNM for rice (Witt et al. 2007).

Nutrient harvest indices are used to determine nutrient balances when fractions of the crop residues are retained in the field (see equations 5 and 6). The median nutrient harvest indices obtained from NPK fertilizer plots were 0.63 for N, 0.69 for P, and 0.15 for K (Table 4). These values for rice are consistent with reports that grain contains about 60% of the N, 15% to 20% of the K, and about two-thirds of the P accumulated in above-ground biomass (Dobermann and Fairhurst 2000).

Nutrient balances in rice-based cropping systems

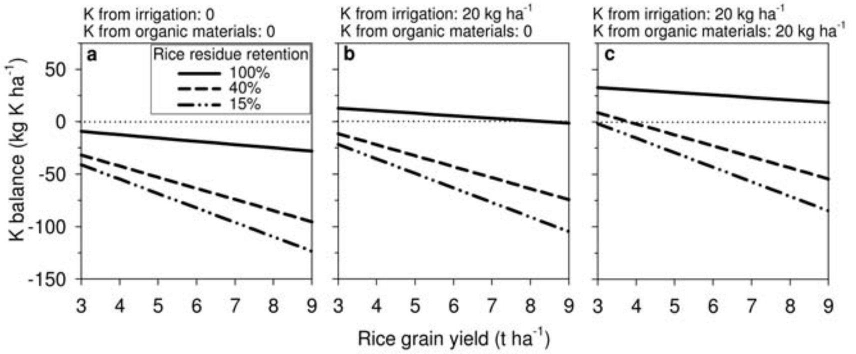
Continuous rice cropping

Continuous rice cultivation with two or three rice crops per year is common across the tropics of Asia. Rice yields in farmers' fields in the tropics can often reach 7 to 8 t ha^{-1} with good agronomic practices in dry seasons with high solar radiation and ample irrigation water. Rice yields in wet seasons typically achieve only 4 to 6 t ha^{-1} with good agronomic practices because of reduced solar radiation and reduced yield potential due to cloudiness. The potential depletion of soil K reserves due to removal of crop residues is a concern in intensive rice cropping (Dobermann and Fairhurst 2000).

The net export of K during rice cultivation with complete retention of crop residue is relatively small even at high grain yields, but removal of crop residues results in substantial export of K (Fig. 3a). Rice in Asia is commonly harvested manually, and the harvested biomass is then transported to a central location for threshing. Within Southeast Asia, some standing biomass (i.e., stubble) is typically retained in the field at harvest, but in South Asia it is relatively common for rice to be harvested near ground level with little retention of standing biomass in the field.

The K balances in Fig. 3 with 15% retention of crop residue represent the frequent situation in South Asia where rice is harvested near ground level, and crop residue after threshing is not returned to the field but rather used for alternative purposes such as fodder, fuel, or bedding for animals. Under such conditions, the crop removal of K increases with increasing grain yield and exceeds 100 kg K ha^{-1} above 7 t ha^{-1}. The K balances in Fig. 3 with 40% retention of crop residue represent the frequent situation in Southeast Asia, where some standing biomass is retained in the field at harvest, but crop residue after threshing is not returned to the field. Combine harvesting with complete retention of crop residue within fields is practiced in some parts of Asia, and it will likely increase in importance, especially where the supply of labor is limited.

Fig. 3 Potassium balances for one rice crop across a range of grain yields as affected by amount of crop residue retained (a), addition of 20 kg K ha^{-1} with irrigation water (b), and addition of an additional 20 kg K ha^{-1} from organic materials (c)

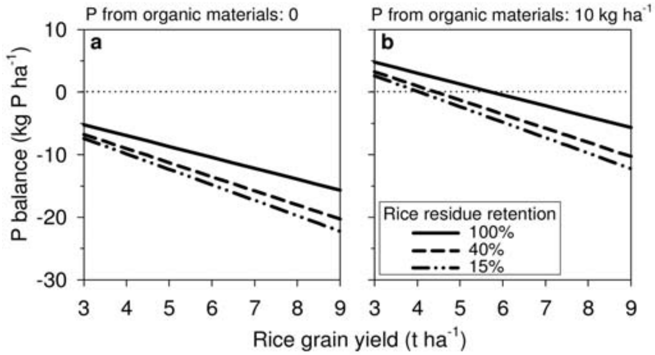


The K balances in Fig. 3 with 100% retention of crop residue represent fields with combine harvesting without subsequent removal of crop residue. They also represent fields with manual harvesting and complete return of crop residue to the field after threshing. The burning of rice residues, though increasingly banned for environmental reasons, is still practiced in some locations. Burning of rice residue spread across a field normally does not result in appreciable loss of K (Dobermann and Fairhurst 2000); hence, burning of rice residue is neglected as a factor in the determination of K balances in this study.

The K balances assume negligible leaching loss in Fig. 3 (K_L in equation 1). Rice soils in Asia are typically tilled at or near saturated soil water content during land preparation by a process called puddling, which destroys soil structure and reduces percolation rate and leaching loss of ions, including K (Sharma and De Datta 1986). My Hoa et al. (2006) reported only 1 to 3 kg K ha^{-1} loss by leaching during a growing season on puddled soil in the Mekong Delta of Vietnam. The input of K from rainwater by comparison was 6 to 10 kg ha^{-1}. Witt and Dobermann (2004) estimated 11 kg K ha^{-1} loss by leaching and 5 kg K ha^{-1} input from rainwater in an approximation of K balances for a typical irrigated rice crop in Asia. Percolation rate and leaching loss are higher on coarse-textured soil with low cation exchange capacity (Bijay-Singh et al. 2004), but such soils are much less common for rice–rice cropping systems. We therefore assume that leaching loss of K approximately matched K input from rainwater and could be treated as negligible.

Phosphorus balances, unlike K balances, in continuous rice cultivation are not strongly affected by management of rice residue (Fig. 4a). Only about one-third of the total P in a mature rice plant typically remains in the crop residue after harvest (Dobermann and Fairhurst 2000). The retention of crop residue has only a small effect on net crop removal of P. All crop residue from rice with 7 t ha^{-1} grain yield contains only about 5 kg P ha^{-1}.

Fig. 4 Phosphorus balances for one rice crop across a range of grain yields as affected by crop residue retention (a) and addition of 10 kg P ha^{-1} from organic materials (b)



Irrigation water from both gravity-fed systems and tube wells typically contains K, and irrigation can represent an important input of K during rice production. The input of K with irrigation water depends on both the K concentration in added water and the quantity of water added during the entire cropping cycle in rice production from the onset of land preparation to harvest. The concentration of K in irrigation water, as shown in Table 7, varies within and among rice-growing areas. The median concentration of K in irrigation water collected from eight rice-growing areas across six countries across Asia ranged from 1.2 to 3.9 mg L^{-1}. When all 245 observations across the eight rice-growing areas were combined, the median K concentration was 1.8 mg L^{-1} and the mean K concentration was 2.5 mg L^{-1} (Table 7).

Table 7 Potassium concentration of irrigation water collected from canals of gravity-fed irrigation systems and from tube wells in rice–rice cropping systems across Asia

Country	Location	Source of water	n[a]	K concentration (mg L^{-1})				
				Mean	SDb	25% quartile	Median	75% quartile
China[c]	Zhejiang	Canal	65	2.1	2.0	1.1	1.7	2.2
India[c]	Cauvery Delta	Well	24	2.6	2.1	1.3	1.8	3.0
Indonesia[c]	West Java	Canal	22	4.0	5.4	1.7	1.9	3.3
Philippines	Bohol	Canal	13	1.1	0.4	1.2	1.2	1.4
	Iloilo	Canal	22	3.8	1.1	3.3	3.9	4.2
Thailand[c]	Central Plain	Canal	20	2.0	0.8	1.6	1.8	2.0
Vietnam[c]	Red River Delta	Canal	31	2.7	2.0	1.2	2.0	3.3
	Mekong Delta	Canal	48	2.0	1.7	1.1	1.8	2.3
All data			245	2.5	2.4	1.3	1.8	2.8

[a] n = number of observations

[b] b SD = standard deviation

[c] Unpublished data from IRRI Reversing Trends in Declining Productivity project, 1997-2000

The total water input from rainfall plus irrigation for one rice-growing cycle can vary from as little as 400 mm for heavy clay soil with shallow groundwater tables that supply water to rice by capillary rise to more than 2000 mm for coarse-textured soil with deep groundwater tables. About 1300 to 1500 mm is a general value for irrigated rice in Asia (Bouman and Tuong 2001; Bouman et al. 2006). Rainfall can differ markedly between growing seasons in Asian rice production areas with two or three rice crops per year. During monsoonal wet seasons, much of the required water can be provided through rainfall. Some irrigated rice areas do not even receive irrigation in the wet season. In the dry season, on the other hand, much of the water must be supplied through irrigation.

We assume an addition of 1000 mm of irrigation water during one cropping cycle. The addition of 1000 mm of irrigation water with 1.8 mg K L^{-1}, the median K concentration in Table 7, would add 18 kg K ha^{-1}. This input of K would increase with increased use of irrigation water, and it would decrease as rainfall contributed a greater portion of the total required water.

The variability in K concentration of irrigation water leads to uncertainty in the input of K for a specific rice field. Results for the two locations in the Philippines in Table 7 illustrate substantial variation in K concentration among locations within a country. The K concentration in irrigation water ranged from

0.3 to 1.5 mg L^{-1} for 13 samples from Bohol and from 2.0 to 6.1 mg L^{-1} for 22 samples from Iloilo (data not shown). The K concentration for 50% of the samples was 1.2 to 1.4 mg L^{-1} in Bohol and 3.3 to 4.2 mg L^{-1} in Iloilo. Assuming an addition of 1000 mm of irrigation water, K input for 50% of the rice fields would be 12 to 14 kg K ha^{-1} in the sample area in Bohol and 33 to 42 kg K ha^{-1} in the sample area in Iloilo. The K inputs for the remaining 50% of rice fields would fall outside these ranges. The deficit in K balances, and consequently the amount of fertilizer K needed to maintain a non-negative K balance, would differ by about 20 to 30 kg K ha^{-1} between Bohol and Iloilo at comparable rice yields and fractions of retained rice residue.

Results in Table 7 also illustrate substantial variability in K concentration of irrigation water within a rice-growing area. In the case of the Cauvery Delta in India, the K concentration in irrigation water for 24 samples ranged from 1.0 to 9.5 mg L^{-1} (data not shown), and 50% of the samples fell within 1.3 to 3.0 mg L^{-1}. Assuming an addition of 1000 mm of irrigation water, K input for rice fields would range from 10 to 95 kg ha^{-1} in the sample area with 50% of the fields receiving 13 to 30 kg ha^{-1}. This variability within a rice-growing area highlights the importance of information on K inputs from irrigation water when determining field-specific fertilizer K rates based on K balances.

The K balances in Fig. 3b assume input of 20 kg K ha^{-1} from irrigation water, which, based on results in Table 7, appears likely for irrigated rice in seasons with limited rainfall. Complete retention of crop residue with such input of K from irrigation water results in near neutral K balances even at high rice yields. This suggests that K deficiency is unlikely in continuous cultivation of irrigated rice with continual retention of all rice residue, use of irrigation water containing $\geqslant 2$ mg K L^{-1}, and negligible K loss by leaching.

Irrigation water normally contains negligible P. The P concentration in irrigation water samples reported in Table 7 was consistently <0.1 mg L^{-1} (data not shown). Irrigation water is consequently not considered a source of significant P in rice–rice cropping systems.

Integrated use of organic materials with manufactured chemical fertilizers is recommended in some rice-growing areas (Mamaril et al. 2009). Organic materials such as composted animal manure and green manures contain K (Witt et al. 2007; Mamaril et al. 2009), which contribute to K balances and the supply of plant-available K to rice crops. The K balances in Fig. 3c assume input of 20 kg K ha^{-1} from organic material, corresponding to 2 t ha^{-1} with 10 g K kg^{-1}, in addition to 20 kg K ha^{-1} from irrigation water. The K deficits and hence likely need for fertilizer K are greatest at high rice yields, especially when little or no crop residue is retained.

Organic materials at common levels of availability and application are unlikely to eliminate deficits in K balances at relatively high rice yields when crop residue is only partially retained. But, at lower rice yields such as <5 t ha^{-1}, which are common for wet seasons, the application of organic materials with partial retention of crop residues can result in near neutral K balances (Fig. 3c). When all crop residue is retained, the application of organic materials can result in positive K balances across all rice yields (Fig. 3c).

The P from added organic materials can have a marked effect on P balances. The input of 10 kg P ha^{-1} from organic material, corresponding to 2 t ha^{-1} with 5 g P kg^{-1}, can eliminate deficits in P balances at rice yields of <5 t ha^{-1} (Fig. 4b). Organic P in added organic materials must be converted to phosphate during decomposition of the organic material to become plant available. As a result of this delayed release of plant-available P from organic materials, a relatively smaller fraction of added P from organic material than from manufactured chemical fertilizer would likely be taken up by rice in the season when P is applied.

Rice–wheat system

The rice–wheat cropping system is common in the subtropics of South Asia and China. It is the main cereal system in the Indo-Gangetic Plains (IGP) of South Asia, where it is practiced on 13.5 million ha across Bangladesh, India, Nepal, and Pakistan. In the northwestern part of the IGP, the rice–wheat system is highly intensive with liberal and often excessive use of irrigation water. There are increasing concerns regarding the sustainability of the system in the northwestern IGP due to low use-efficiency of inputs, including fertilizers, depletion of irrigation water, and degradation of soil resources (Ladha et al. 2009).

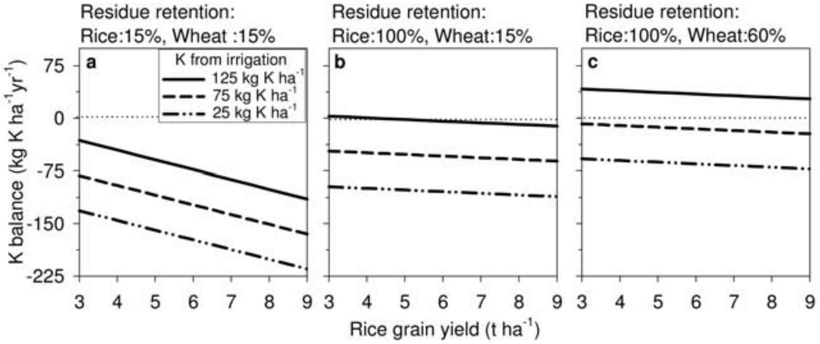
In Northwest India, within the northwestern part of the IGP, the groundwater used for irrigation of rice–wheat is relatively high in K. Reported K concentrations for 242 samples from tube wells in the central plain region of the state of Punjab in Northwest India ranged from 0.87 to 38.2 mg L^{-1} with a mean of 5.1 mg L^{-1} (Pasricha et al. 2001). This corresponded to an estimated input of about 80 kg K ha^{-1} from irrigation water for a rice–wheat system. Canal water from gravity-fed irrigation is relatively lower in K content than water from tube wells. Because some farmers use water from both sources during a rice–wheat cropping cycle (Erenstein 2009), the input of K with irrigation water depends on source as well as the amount of added water.

Soils for rice–wheat cropping in the northwestern IGP are light textured with rapid loss of water by percolation. An abundance of electric and diesel tube wells has enabled considerable extraction of groundwater for rice–wheat production (Erenstein 2009). A survey of farmers at sites in Haryana, India and Punjab, Pakistan revealed use of about 1600 to 1900 mm irrigation water during one rice production cycle (Erenstein 2009). Much less irrigation water, approximating

200 to 300 mm, is used for wheat production (Khurana et al. 2008; Erenstein 2009). Use for one rice–wheat cropping cycle of an estimated 2000 mm irrigation water originating from a tube-well with 5.1 mg K L^{-1} would result in input of 102 kg K ha^{-1} from tube well irrigation. This matches with an estimated 100 kg K ha^{-1} yr^{-1} from irrigation water reported in a long-term rice–wheat experiment at Ludhiana, Punjab, by Bijay-Singh et al. (2004) in a review of literature. A fraction of the added K would likely be lost from the crop rooting zone through leaching. An annual input of 75 kg K ha^{-1} from irrigation water is therefore used in Fig. 5 as a plausible net K input for a typical rice–wheat cropping system in Northwest India.

Soil K in addition to K from irrigation water can be lost by leaching. Leaching loss of soil K can be an important output in K balances on soils with relatively high release of K from nonexchangeable pools and minerals, leading to high concentrations of K in soil solution lost by percolation (Haefele 2001). Bijay-Singh et al. (2004), in a review of literature, estimated an annual K leaching loss of 19 to 31 kg ha^{-1}, depending on inputs of K, from a rice–wheat system on light-textured soil in Punjab. The estimated annual K input from rainwater was 5 kg ha^{-1}. Annual leaching loss of 20 kg K ha^{-1} is therefore used in Fig. 5 to approximate total leaching loss of soil K minus the small input of K from rainwater.

Fig. 5 Potassium balances for one rice–wheat cropping cycle in Northwest India across a range of rice grain yields as affected by net input of K with irrigation water and amount of crop residue retained. Wheat grain yield is 5 t ha^{-1} in all cases



As reported by Pasricha et al. (2001), K concentrations in tube-well water can be markedly higher than 5 mg L^{-1}. Assuming an application of 1800 mm of water with 10 mg K L^{-1} and leaching loss of about 30% of the added K, this would result in a net input of about 125 kg K ha^{-1}, which is included in Fig. 5 as a plausible high net input of K with irrigation water. The low net K input of 25 kg ha^{-1} in Fig. 5 represents the use of water-saving technology leading to substantial savings in total water use, enabling the use of primarily canal water rather than tube-well water for irrigation.

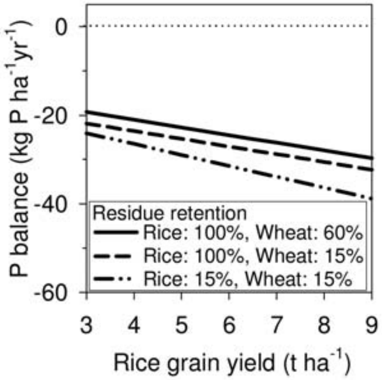
Wheat residue is often removed from the field for use as fodder in Northwest India, whereas rice residue is less valuable for fodder and is often partially or completely retained in the field (Mandal et al. 2004). The K balances in Fig. 5a with 15% retention of both rice and wheat residue represent removal of all aboveground crop biomass except for small standing biomass near ground level. Under such conditions, K balances are negative across all rice grain yields even with high input of K from irrigation water.

The K balances in Fig. 5b with 15% retention of wheat residue and 100% retention of rice residue represent a relatively common situation with removal of wheat residue but complete retention of rice residue such as after combine harvesting. Under such conditions, the K balance is near neutral across all rice grain yields with net input of 125 kg K ha^{-1} from irrigation water. Annual K balances are somewhat negative (–50 to –60 kg K ha^{-1}) with a plausible common net input of 75 kg K ha^{-1} from irrigation water. Soils in this region have an inherent capacity to release K (Bijay-Singh et al. 2004). The retention of some crop residue, use of relatively large amounts of irrigation water from tube wells, and net release of K from soil reserves could contribute to the commonly observed absence of crop response to applied K (Khurana et al. 2008). The burning of rice residue would likely not have much effect on the K balances because residue spread across a field normally does not result in appreciable loss of K (Dobermann and Fairhurst 2000).

The use of water-saving technologies that markedly reduce K inputs from irrigation (e.g., input = 25 kg K ha^{-1} in Fig. 5b) would result in more negative K balances, suggesting that water-saving technologies could increase the likelihood of K deficiency even when rice residue is retained. Water-saving technologies could be combined with retention of wheat residue (Fig. 5c) or use of fertilizer K to compensate for reduced input of K from irrigation water. The value of wheat residue for fodder and uses other than a supply of K would need to be assessed relative to the cost of fertilizer K to determine the potential attractiveness of wheat residue as a source of K. Our analysis suggests that variation in irrigation and residue management among fields can strongly affect K balances, which could have a considerable effect on the estimation of field-specific fertilizer K rates in the rice–wheat system.

The P balances in the rice–wheat system are consistently negative regardless of the quantity of retained crop residue (Fig. 6). The retention of crop residue has less effect on P than K balances because a much smaller fraction of the plant P than K remains in crop residue after harvest. The net removal of P in one cropping cycle with 5 t ha^{-1} wheat grain yield and 7 t ha^{-1} rice grain yield is about 30 kg ha^{-1}. This matches closely with results of on-station research at Ludhiana, Punjab, that led to recommended application of 26 kg P ha^{-1} to wheat that responds to P and no application of P to rice that typically does not respond to P (Gupta et al. 2007).

Fig. 6 Phosphorus balances for one rice–wheat cropping cycle in Northwest India across a range of rice grain yields as affected by amount of crop residue retained. Wheat grain yield is 5 t ha^{-1} in all cases

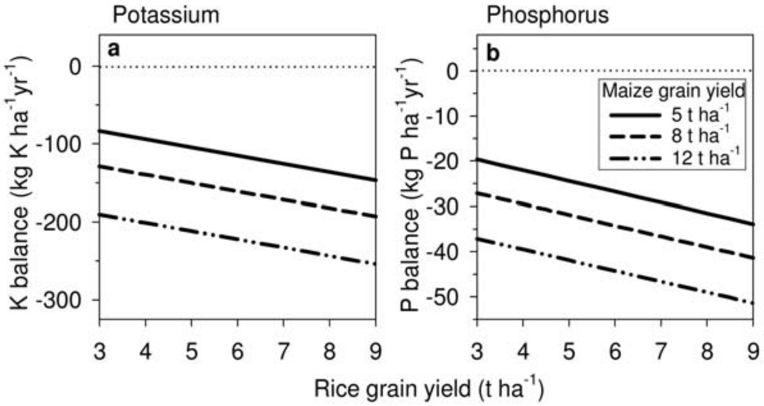


Rice–maize system

The rice–maize cropping system in irrigated lowlands is gaining importance across tropical and subtropical Asia in response to increasing demand of maize for feed and biofuel. Rice is a well-adapted crop in lowlands in the wet season, but maize can replace rice in the drier or cooler season, especially when marketing opportunities are attractive for maize or irrigation water is limited for rice production (Ali et al. 2008).

The nutrient balances for one rice–maize cycle in Fig. 7 represent common management for a rice–maize system with removal of nearly all above-ground biomass (residue retention = 15%) and retention of some standing rice biomass after harvest (residue retention = 40%). Maize residue is typically not retained because it is difficult to incorporate during tillage for rice production and the incorporated residue with its high C-to-N ratio can lead to immobilization of N during decomposition. The K input from irrigation water is assumed to be only 25 kg ha^{-1} because the rice–maize system, unlike rice–wheat in Northwest India, is not common in areas with high application to rice of tube-well water high in K. Leaching loss of K is assumed to be negligible.

Fig. 7 Potassium and phosphorus balances for one rice–maize cropping cycle across a range of rice grain yields as affected by maize yield. In each case 40% of rice residue and 15% of maize residue were retained in the field, and K input from irrigation water during the cropping cycle was 25 kg ha^{-1}

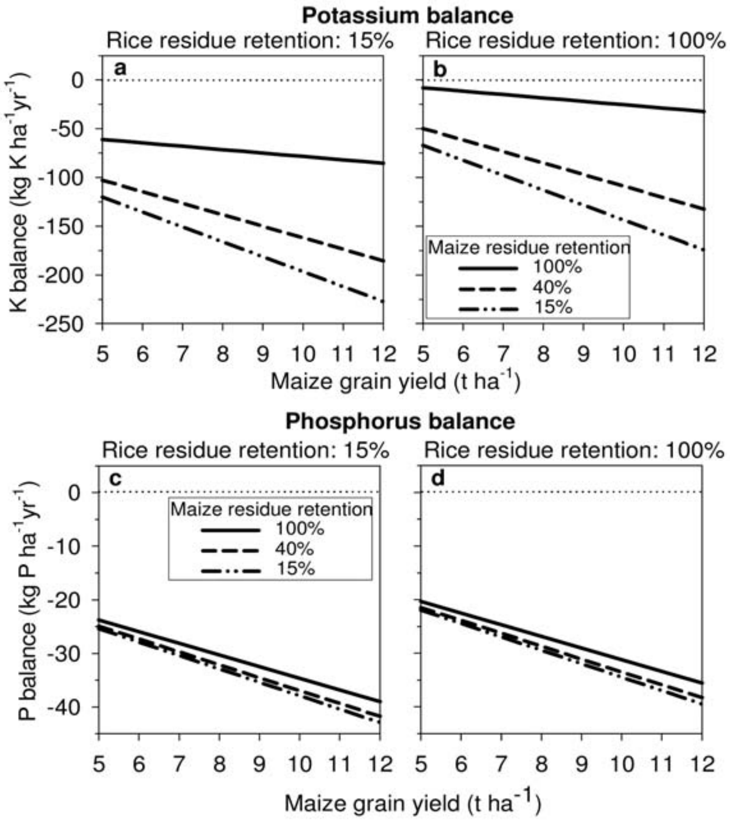


Nutrient balances for the rice–maize system are strongly affected by the yield of maize (Fig. 7). Hybrid maize in a rice–maize system can achieve a yield up to 12 t ha^{-1} with good management practices and a sufficient supply of nutrients in farmers' fields (IPNI, unpublished data), which is markedly higher than the achievable yield for either rice or wheat in the same season. At 12 t ha^{-1} maize grain, there is a net export of about 200 kg K ha^{-1} and 40 kg P ha^{-1} for one rice–maize cropping cycle with common residue management practices and production of 5 t ha^{-1} rice grain (Fig. 7). The rice–maize system with high maize yield is more extractive of nutrients than rice–rice and rice–wheat systems.

The retention of maize residues can markedly reduce the net export from a rice–maize cropping system of K but not P (Fig. 8). In the rice–maize cropping system, rice is typically grown in the wet season when rice yield is often lower than in the dry season. The nutrient balances in Fig. 8 consequently assume a rice yield of only 5 t ha^{-1} in the wet season. Retention of maize residues markedly reduces but does not eliminate the deficit in K balances when rice residue is not retained (Fig. 8a). Retention of all maize and rice residues is required to achieve near-neutral K balances (Fig. 8b).

Retention of rice residues is feasible through either combine harvesting or manual harvesting with retention of standing biomass. Retention of maize residue is problematic because it increases the energy required for tillage before rice. Incorporation of maize residue due to its high C-to-N ratio can also have short-term negative effects on N availability to rice due to N immobilization (Buresh et al. 2008). Establishment of rice with mulching of the maize residue

Fig. 8 Potassium and phosphorus balances for one rice–maize cropping cycle across a range of maize grain yields as affected by amount of maize and rice residue retained. Rice grain yield was 5 t ha^{-1} in all cases, and K input from irrigation water during the cropping cycle was 25 kg ha^{-1}



rather than tillage to incorporate maize residue, such as through direct dry seeding, might provide an alternative to facilitate retention of maize residues in the rice–maize system. In the absence of technologies to facilitate retention of maize residue, higher K deficits and hence higher fertilizer K requirements are likely for the rice–maize system with high-yielding hybrid maize than for the rice–rice or rice–wheat system.

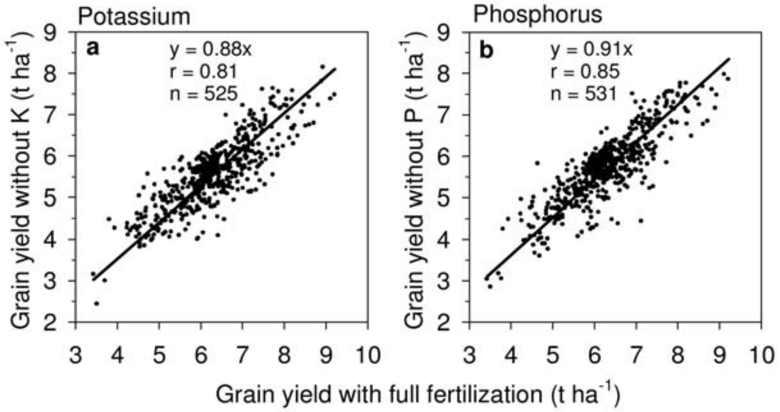
The P balances are affected more by maize yield than by management of maize and rice residues. The P deficits and hence likely need for fertilizer P increase in direct proportion to the yield of maize (Fig. 8cd).

Determination of fertilizer K and P rates

Yield gain approach

Results from over 500 on-farm nutrient omission trials conducted with irrigated rice in Bangladesh, India, Indonesia, and Vietnam (Table 1) are presented in Fig. 9 to provide an example of yield gains attainable for rice from K and P fertilization in Asia. Grain yields without K or without P increased in direct proportion to yields with full fertilization throughout the range in yields from 3 to 9 t ha^{-1}. Yield gains expressed as a fraction of the yield with full fertilization averaged 12% (slope = 0.88) for K and 9% (slope = 0.91) for P.

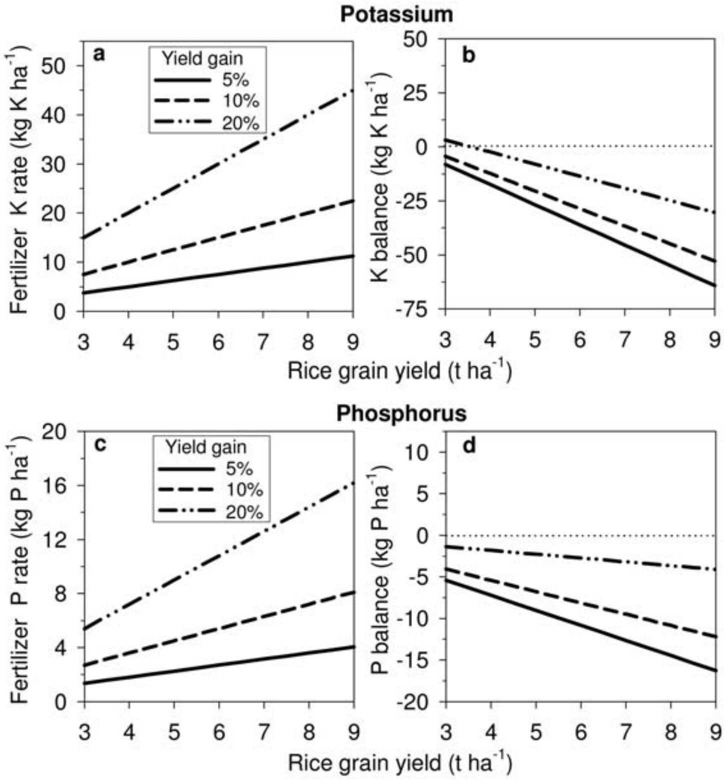
Fig. 9 Relationship between rice grain yields in a plot with full fertilization of ample N, P, and K and an adjacent plot without application of K or P but sufficient amounts of other nutrients to prevent their limitations. Data are from trials conducted in farmers' fields in Bangladesh, India, Indonesia, and Vietnam



In the yield gain approach for determining fertilizer K and P requirements, fertilizer K and P are applied only when a crop response to the nutrient is certain. As shown in Fig. 9, the yield gain for irrigated rice from added K or P is often relatively small to moderate, averaging near 10%. We therefore present yield gains of 5%, 10% and 20% in an illustration of fertilizer K and P rates and balances across the feasible range of irrigated rice yields from 3 to 9 t ha^{-1} (Fig. 10).

Fertilizer K and P rates were determined using equations 7 and 8 in which yield gain ($GY - GY_0$) at a targeted yield with full fertilization (GY) was determined as the respective fraction (5%, 10%, or 20%) of GY. We used RIEs for K (15.9) and P (2.7) as determined by QUEFTS (Table 3) and recovery efficiencies

Fig. 10 Fertilizer K and P rates for rice determined with a yield gain approach based on anticipated yield gain from K or P fertilization, expressed as a percentage of the attainable yield with full balanced fertilization. In each case 40% of rice residue was retained in the field, and K input from irrigation water during the cropping cycle was 20 kg ha^{-1}



of K ($RE_K = 0.64$) and P ($RE_P = 0.3$) that correspond to about the 70% quartile for values obtained by Witt and Dobermann (2004) from a large data set for irrigated rice in Asia. Fertilizer requirements corresponded to 25 kg K ha^{-1} and 9 kg P ha^{-1} to raise the respective nutrient-limited yield by 1 t ha^{-1}. In the estimation of K and P balances in Fig. 10, we assumed 40% retention of rice residue (CRR = 0.4 in equations 5 and 6) and 20 kg K ha^{-1} net input from irrigation water, which approximates a likely median value for dry-season rice among sites shown in Table 7. Leaching loss of K is assumed to be negligible.

Fertilizer K and P requirements determined by the yield gain approach (equations 7 and 8) increased with increasing target yield (Fig. 10ac), but the K and P rates did not increase sufficiently fast to prevent increasing depletion of soil fertility with increasing yield within the ranges of yield gain common for irrigated rice (Fig. 10bd). The same trends of increasing fertilizer rates and decreasing nutrient balances with increasing yield occur when lower recovery efficiencies ($RE_K = 0.35$ and $RE_P = 0.22$) corresponding to median values reported by Witt and Dobermann (2004) were used to determine fertilizer requirements (data not shown).

A distinctly undesirable feature of fertilizer K and P rates determined by the yield gain approach is higher K and P depletion at high than low target yields. This could accelerate the onset of nutrient limitations and subsequent declines in productivity in existing high-yielding areas. For both K and P, the slope for estimated nutrient balances with increasing yield became less negative as yield gain increased from 5% to 20%. Yield gains >20%, which are not common for irrigated rice (Fig. 9), would be required to obtain slope = 0 (Fig. 10), at which point nutrient depletion would be constant across yields.

Although Fig. 10 presents results for rice, the same trends would apply to wheat and maize. Cereal-growing areas with high-yielding crops and relatively small current yield gain from K and P fertilization — and hence low fertilizer K and P recommendations based on a yield gain approach — would be particularly prone to nutrient mining and risk of declining productivity. For K, because of the large portion of total plant K in crop residues, the risk would be greater in high-yielding fields with removal than with retention of crop residues. Locations with existing large yield gains from K and P fertilization would be relatively less at risk of further K and P mining from fertilizer K and P recommendations based solely on a yield gain approach.

The determination of fertilizer K (FK) or fertilizer P (FP) (in kg ha^{-1}) required to achieve a targeted yield (GY, expressed in t ha^{-1}) by the yield gain approach can be simplified by replacing RIE/RE in equations 7 and 8 with a target agronomic efficiency (AE) for the nutrient:

$$FK = (GY - GY_{0K}) \times 1000/AE_K \qquad [19]$$

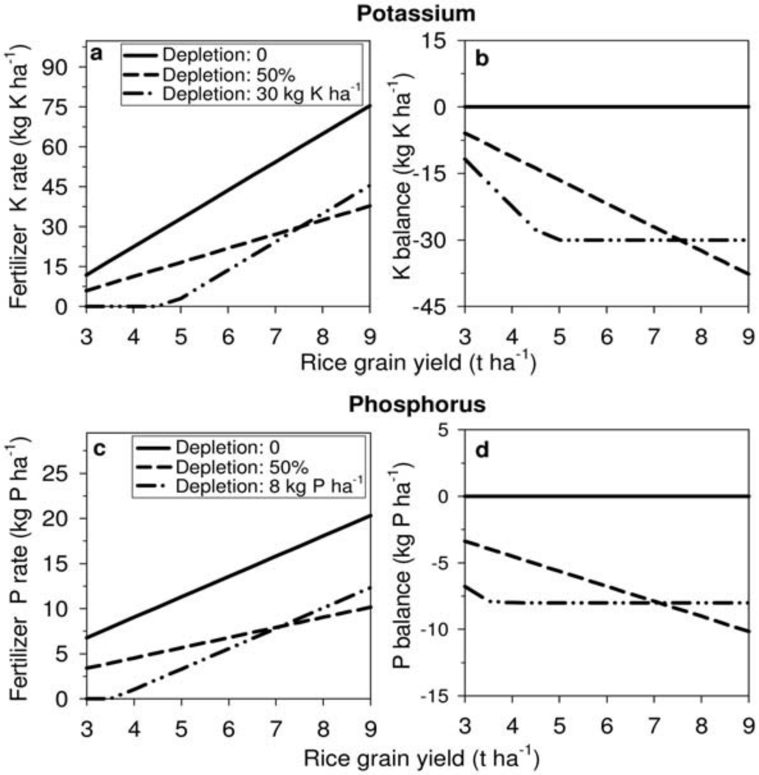
$$FP = (GY - GY_{0P}) \times 1000/AE_P \qquad [20]$$

where agronomic efficiency of the applied nutrient (AE_K or AE_P) is expressed as kg increase in grain yield per kg applied nutrient. The determination with SSNM of fertilizer N requirements uses a comparable yield gain approach with agronomic efficiency (Witt et al. 2007). The target fertilizer requirements of 25 kg K and 9 kg P to raise the respective nutrient-limited yield by 1 t ha^{-1} correspond to $AE_K = 40$ kg kg^{-1} and $AE_P = 110$ kg kg^{-1}. This AE_P is derived from a data set without P-fixing soils, and it would likely be lower for soils with high capacity to fix P.

Nutrient maintenance based on nutrient balance approach

The nutrient balance approach based on full or partial maintenance of nutrient input-output balances provides an alternative to the yield gain approach for determining fertilizer K and P requirements. With full maintenance (FM = 1 in equations 11 and 12), the fertilizer K or P rates match removal of K or P, ensuring no nutrient depletion (depletion = 0 in Fig. 11). Full maintenance rates of a nutrient fail to consider enhanced nutrient availability from soil biological, chemical, and physical processes. They can also result in short-term financial loss for farmers when the yield gain resulting from application of the nutrient is negligible or small. But, failure to apply the nutrient leads to nutrient depletion, which might eventually lead to yield loss. Application of fertilizer K and P at less than full (i.e., partial) maintenance rates could then provide an opportunity to consider the supply of nutrient from soil reserves, including contributions from biological processes, and better handle the tradeoffs between longer-term sustained productivity and short-term financial benefit.

Fig. 11 Fertilizer K and P rates for rice determined with a nutrient balance approach allowing three contrasting amounts for K and P depletion. In each case 40% of rice residue was retained in the field, and K input from irrigation water during the cropping cycle was 20 kg ha^{-1}



One option for determining fertilizer rates at partial maintenance is to allow a drawdown or depletion of soil nutrient reserves equivalent to a fraction of the nutrient required for full maintenance of the nutrient input-output balance. This option, which we refer to as fractional depletion, is illustrated in Fig. 11 for fertilizer K and P rates determined at 50% of full maintenance (depletion = 50%; FM = 0.5 in equations 11 and 12). Fertilizer rates increased with increasing target yield (Fig. 11ac), but the K and P rates did not increase sufficiently fast to prevent increasing depletion of soil K and P with increasing yield (Fig. 11bd). Nutrient depletion and risk of declining productivity are higher at high than low target yields with this option of partial maintenance.

Another option for determining fertilizer rates at partial maintenance is to allow depletion of a nutrient up to but not beyond a threshold limit (K_S and P_S in equations 13 and 14). In this option, which we refer to as limited depletion, the threshold limit represents the estimated drawdown of soil nutrient reserves that could be sustained without leading to more nutrient limitations on crop yield. The allowable drawdown of soil nutrient reserves (FM in fractional depletion option and K_S and P_S in limited depletion option) could depend upon soil processes like soil biological activity as affected by water regime (Turner and Haygarth 2001) and tillage (Lorenz et al. 2009), equilibrium among nutrient pools (Singh at el. 2002; Saleque et al. 2009), and soil characteristics like mineralogy (Bijay-Singh et al. 2004). Fig. 11 illustrates conditions in which the limits for drawdown of soil nutrient reserves were 30 kg K ha^{-1} (K_S) and 8 kg P ha^{-1} (P_S). Rice residue retention was 40%, net K input from irrigation water was 20 kg ha^{-1}, and leaching loss of K was negligible.

With the limited depletion option, fertilizer rates (Fig. 11ac) are calculated such that nutrient balances (Fig. 11bd) are never more negative than the limit for drawdown of soil nutrient reserves (K_S and P_S). No fertilizer K or P is recommended at low yields (Fig. 11bd). Fertilizer K or P is recommended only above the yield at which the net output of the nutrient in the nutrient balance exceeds K_S or P_S (equations 13 and 14). The relatively comparable level of nutrient depletion across yields and the absence of increasing nutrient depletion at high yields make the limited depletion option for partial maintenance (equations 13 and 14) more attractive than the fractional depletion option (equations 11 and 12) for determining fertilizer K and P across environments with widely varying yields.

Partial maintenance plus yield gain approach

Use of the partial maintenance approach to determine fertilizer requirements risks applying insufficient nutrient to meet crop needs when yield gain to the added nutrient is large, but use of the yield gain approach by itself can result in nutrient depletion at high yields (Fig. 10bd). A combination of the two approaches was therefore examined for determining fertilizer requirements when yield gain from added nutrient is certain.

In Fig. 12 the fertilizer K and P rates and balances for a partial maintenance approach with limited depletion (K_S = 30 kg K ha^{-1} and P_S = 8 kg P ha^{-1}) are compared alone (equations 13 and 14) and in combination with a yield gain approach (equations 17 and 18). Yield gain was either set at 20% of attainable yield ($GY - GY_0 = 0.2GY$) or at a constant 1 t ha^{-1} ($GY - GY_0 = 1$). In Fig. 13 the fertilizer K and P rates and balances for a partial maintenance approach with fractional depletion (depletion = 50%, FM = 0.5) are compared alone (equations 11 and 12) and in combination with a yield gain approach (equations 15 and 16). As in Fig 12, yield gain was either set at 20% of attainable yield or at a constant 1 t ha^{-1}. As in Fig. 10 and Fig. 11, rice residue retention was 40%, net K input from irrigation water was 20 kg ha^{-1}, and leaching loss of K was negligible.

Fig. 12 Fertilizer K and P rates for rice determined with a partial maintenance plus yield gain approach in which maximum K and P depletion does not exceed a threshold limit from the soil nutrient reserves. In each case 40% of rice residue was retained in the field, and K input from irrigation water during the cropping cycle was 20 kg ha^{-1}

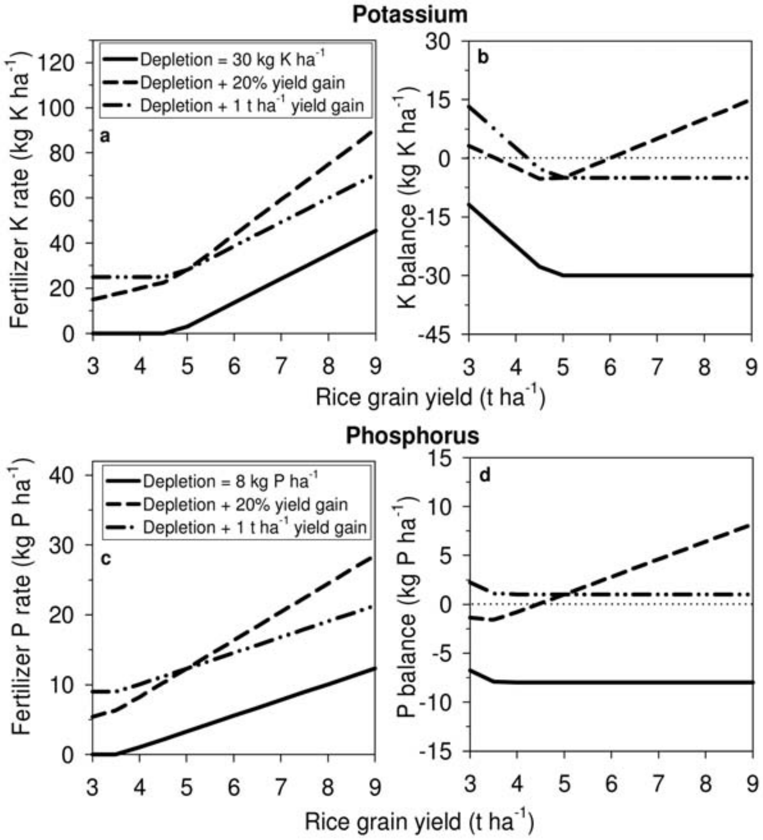
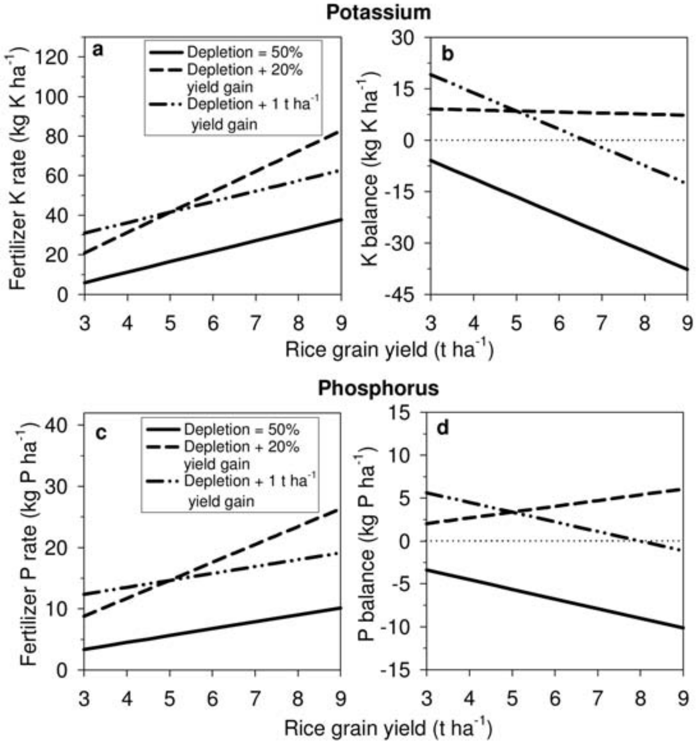


Fig. 13 Fertilizer K and P rates for rice determined with a partial maintenance + yield gain approach in which maintenance rates of K and P are a fraction of the nutrient depletion determined with nutrient balances. In each case 40% of rice residue was retained in the field, and K input from irrigation water during the cropping cycle was 20 kg ha^{-1}



Fertilizer rates were lowest when determined with only a partial maintenance approach (Fig. 12ac and 13ac). Combining partial maintenance with a yield gain approach resulted in higher calculated fertilizer rates and more positive K and P balances (Fig. 12bd and 13bd). Fertilizer rates with a partial maintenance plus yield gain approach increased faster with increasing yield when yield gain was expressed as a fraction of attainable yield (i.e., 20%) rather than as a fixed amount (i.e., 1 t ha^{-1}). The K and P balances as a result were more positive at higher yields when yield gain was expressed as a fraction of attainable yield (i.e., 20%).

Based on results from nutrient omission plot studies (Fig. 9), the yield gain of rice from K and P fertilization is directly related to the attainable yield with full fertilization. Yield gain is consequently better represented across a wide range of yields as a fraction of the attainable yield (i.e., 20% in Fig. 12 and 13) rather than a fixed amount (i.e., 1 t ha^{-1}). Based on data in Fig. 9, for example, at 5 t ha^{-1} attainable yield with full fertilization, the mean yield gain was 0.6 t ha^{-1} for K application and 0.5 t ha^{-1} for P application; at 8 t ha^{-1} attainable yield with full fertilization, the mean yield gain was 1.0 t ha^{-1} for K application and 0.7 t ha^{-1} for P application.

The results suggest that at low rice yields when the yield gain from applied K or P is relatively small such as $\leqslant 0.5$ t ha^{-1}, which often corresponds to yields of <5 t ha^{-1} (Fig. 9), fertilizer requirements can be determined with only a partial maintenance approach (Fig. 11). When yield gain is more pronounced, a partial maintenance plus yield gain approach can be considered for determining fertilizer requirements (Fig. 12 and 13). Expressing yield gain as a fraction of targeted yield helps ensure a good fit with measured yield gains (Fig. 9), and it helps ensure that the input of nutrient at higher yields is relatively higher and sufficient to overcome nutrient deficiencies.

The determination of fertilizer K (FK) or fertilizer P (FP) by a partial maintenance plus yield gain approach can be simplified by replacing RIE/RE in equations 15 to 18 with a target agronomic efficiency (AE) of the nutrient. Equations 15 and 16 for the fractional depletion option become:

$$FK = ((GY \text{ x } RIE_K - K_{CR} - K_W - K_{OM} + K_L) \text{ x } FM) + ((GY - GY_{0K}) \text{ x } 1000/AE_K) \quad [21]$$

$$FP = ((GY \text{ x } RIE_P - P_{CR} - P_{OM}) \text{ x } FM) + ((GY - GY_{0P}) \text{ x } 1000/AE_P) \quad [22]$$

Equations 17 and 18 for the limited depletion option become:

$$FK = (GY \text{ x } RIE_K - K_{CR} - K_W - K_{OM} - K_S + K_L) + ((GY - GY_{0K}) \text{ x } 1000/AE_K) \quad [23]$$

$$FP = (GY \text{ x } RIE_P - P_{CR} - P_{OM} - P_S) + ((GY - GY_{0P}) \text{ x } 1000/AE_P) \quad [24]$$

Discussion

The SSNM-based approach and algorithms we present for determining fertilizer K and P requirements provide an alternative to soil-test approaches (Slaton et al. 2009) that use algorithms derived from fertilizer response trials conducted across multiple locations. The SSNM-based approach through the use of nutrient balances enables the determination of fertilizer K and P requirements when the yield gain from the applied nutrient is negligible or uncertain (Witt and Dobermann 2004; Witt et al. 2007), which periodically occurs for irrigated rice especially at lower yields (Fig. 9). In this paper we revise the SSNM-based approach to accommodate partial nutrient balances, which consider the net effect of soil processes and soil characteristics mediating K and P supply when yield gain from the applied nutrient is uncertain. The use of nutrient balances across a full range of plausible yields enables fertilizer K and P requirements to be adjusted for field-specific yield and management, such as amounts of retained crop residue and applied organic materials, which affect inputs and outputs of K and P.

The SSNM-based approach for determining fertilizer requirements is well suited for small, heterogeneous landholdings typical of rice-based cropping systems in Asia where fertilizer requirements can vary greatly among nearby fields and the yield gain from applied K or P is often uncertain. Nutrient balances can provide a pragmatic estimate of nutrient inputs and outputs for a field plot, which can then be used for determining fertilizer K and P requirements for the specific field. Numerous practices including tillage, management of crop residues and organic materials, and water management can influence soil biological activity and nutrient availability. Their net effect on K and P supply can be considered through K_S and P_S in partial nutrient balances (equations 13, 14, 23, and 24). Research is needed to quantify the net effect of soil processes and soil characteristics on the sustainable drawdown of soil K and P reserves (K_S and P_S) used in the determination of fertilizer K and P requirements.

Whereas nutrient balances are essential for determining SSNM-based fertilizer K and P requirements, nutrient balances are not used for determining SSNM-based fertilizer N requirements. With SSNM, fertilizer N requirements are based on the yield gain from applied N (Witt et al. 2007) because rice and other cereal crops in irrigated environments virtually always respond to fertilizer N. The SSNM-based approach enables yield gain from applied fertilizer N, and hence total fertilizer N requirement, to be adjusted for management practices. It also provides decision tools such as the leaf color chart for dynamically adjusting the application of N during the growing season to match crop needs for supplemental N (Alam et al. 2005), which can be influenced by the effects of management on availability of soil N.

Internal nutrient efficiencies for rice

Field-specific requirements of a cereal crop for fertilizer K and P can be calculated using RIE to estimate nutrient accumulation by a crop (Witt and Dobermann 2004). The RIE values obtained for rice in our study using QUEFTS matched well with RIE values reported by others (Witt et al. 1999; Haefele et al. 2003) for rice with harvest index $\geqslant 0.4$, grown with balanced fertilization and good agronomic management. This consistency in RIE across diverse irrigated rice-growing environments and cultivars provides confidence that one RIE per nutrient can be used for semi-dwarf irrigated rice in determining fertilizer P and

K requirements when fertilization is balanced to match crop needs.

Deviations in RIE from the estimation with QUEFTS arise from unbalanced plant nutrition leading to either nutrient accumulation associated with luxuriant uptake of the nutrient or nutrient dilution associated with nutrient deficiency. Deviations in RIE can also arise from biotic or abiotic stresses that adversely affect grain production leading to low harvest index. The desired RIE value for use in determining fertilizer P and K requirements reflects an optimal accumulation of the nutrients in a mature crop without biotic and abiotic stress.

The RIE increases slightly as targeted yield increases above 60% to 70% yield potential, which is common in farmers' fields, to 80% of yield potential, which represents a likely upper limit to profitable rice production (Table 6). But this change in RIE is relatively small ($\leqslant$ 7%) compared to other inherent uncertainties associated with the determination of fertilizer rates such as estimation of the attainable yield, yield gain, and some components of the nutrient balance such as K addition from irrigation water. The use of RIE at 60% to 70% of yield potential therefore appears appropriate for determing fertilizer requirements for irrigated rice.

Semi-dwarf, high-yielding irrigated rice without biotic or abiotic stresses has harvest index $\geqslant$0.4, which was the lower limit of harvest index used by Witt et al. (1999), Haefele et al. (2003), and our study. We propose that 14.6 kg N, 2.7 kg P, and 15.9 kg K per tonne of grain (Table 3) and nutrient harvest indices of HI_K = 0.15 and HI_P = 0.7 (Table 4) obtained from a large data set in our study and comparable to values reported by others (Witt et al. 1999, Haefele et al. 2003) can serve as standards for use in determining nutrient balances and associated P and K fertilizer rates with semi-dwarf, high-yielding irrigated rice grown with good agronomic practices and sufficient water. Alternative RIE values would be required for rice cultivars with harvest index <0.4 (Table 5).

Some rice in rainfed areas can have harvest index <0.4 and corresponding increased accumulation of plant nutrient in above-ground dry matter per tonne grain yield. Mukhopadhyay et al. (2008), for example, in a fertilizer trial with rainfed rice in West Bengal in eastern India, reported mean harvest index = 0.32 and mean accumulation of 33 kg K and 4.3 kg P per tonne of grain. In a multi-location trial in Thailand with 624 observations for traditional tall rice cultivars, Naklang et al. (2006) reported median harvest index = 0.28 and median plant accumulation of 48 kg K and 4.7 kg P per tonne of grain. In both studies the rice yields were relatively low (<4 t ha^{-1}). The higher RIE reported for traditional-type rice by Naklang et al. (2006) than found for semi-dwarf modern rice such as in Witt et al. (1999) and our study resulted from differences in harvest index rather than differences in tissue concentration of nutrients between the two types of rice.

The RIE estimated from the mean or median of a data set (Table 2) tends to be higher than the RIE estimated from the linear portion of the QUEFTS model (Table 3), which reflects a more balanced uptake of nutrient by the crop. We therefore recommend use of the QUEFTS model with a relatively large data set from across rice-growing areas to estimate RIE for rice cultivars with harvest index <0.4. The estimated RIE for K and P can then be used in calculating nutrient balances and fertilizer rates for rice cultivars — for a given range in harvest index — grown with balanced use of nutrient inputs and good agronomic practices. Data from crop-growing situations with either luxuriant uptake of nutrients, such as arising from excessive fertilization, or nutrient deficiency are therefore preferably omitted from the data set used with QUEFTS.

Nutrient balances in rice-based cropping systems

Potassium balances in rice-based systems are strongly affected by the attained crop yield and fraction of crop residue retained, which can vary from field to field. An immediate opportunity for improving the profitability and effectiveness of fertilizer K use is consequently to enable field-specific adjustments in fertilizer K rates based on probable yield and fraction of crop residue retained in a specific field. Fertilizer K rates for a field could then be further adjusted based on the use of externally produced organic materials. Whereas organic materials are often promoted for their N benefit, the K inputs from organic materials can be overlooked. From the perspective of K balances and maintenance of soil K fertility, the application of organic materials to rice is more warranted when crop residues are removed rather than retained. Full retention of rice residue with the application of organic materials can potentially result in positive K balances (Fig. 3c).

Irrigation water can be an unknown but important input of K in rice production because of the large quantity of water applied to rice. Uncertainties associated with K concentration in irrigation water and quantity of added irrigation water, which can vary from field to field, present a challenge for improving K management and adjusting fertilizer K rates for field-specific conditions. The K concentration in irrigation water depends on the source of the water. It is often higher in water from tube wells than from canals in gravity-fed irrigation systems (Pasricha et al. 2001), but it can vary among gravity-fed irrigation systems as illustrated by the contrast between Bohol and Iloilo in the Philippines (Table 7).

The adjustment of fertilizer K requirements to field-specific yields and residue retention can be relatively straightforward because farmers know their field-specific yields and residue management practices. The K input through irrigation water, on the other hand, will not be known to farmers. An adjustment in fertilizer K requirements for inputs from irrigation water would likely need to be made across a region rather than for a specific field. One option could be to estimate, across an entire gravity-fed irrigation system or across all tube wells in a region, a probable net K input based on approximate K concentration of the water and typical amount of irrigation water used in a cropping season. This estimated probable K input could then be used to adjust nutrient balance-based K fertilizer rates across fields for the irrigation system or region. Although such an adjustment in fertilizer K rates would undoubtedly contain much uncertainty, it would be superior to the current situation in which net K input from irrigation water is either ignored or assumed to be constant across a country.

Phosphorus balances in rice and rice-based systems are strongly affected by attained crop yield. Residue retention has relatively little effect on P balances and hence fertilizer P requirements determined through nutrient balances because of the relatively low P content of residue compared with grain. An immediate opportunity for improving the profitability and effectiveness of fertilizer P use is consequently to enable field-specific adjustments in fertilizer P rates based on probable yields.

Fertilizer P rates at the field level could then be further adjusted based on the use of organic materials, which, when relatively rich in P, can contribute to P balances (Fig. 4). Uncertainty exists regarding P supply from organic materials because organic materials can vary greatly not only in P concentration but also in the rate of release of plant-available P. The supply of P from organic materials at least in the short term is probably less than from manufactured chemical fertilizer, in which case one unit of P from organic materials would substitute for less than a comparable unit of P from manufactured chemical fertilizer. The effectiveness in replacing P from manufactured chemical fertilizer might increase, however, through longer-term application of organic materials. Appropriate adjustment in fertilizer P rates for P supplied by added organic materials is consequently a challenge.

High input of K through irrigation water together with supply of K from soil has likely contributed to the long-term production of rice–wheat in Northwest India (Fig. 5) with little or no response to fertilizer K (Khurana et al. 2008). The introduction of practices that markedly reduce the use of tube-well water, such as resource-conserving technologies (Ladha et al. 2009), could lead to more negative K balances and increased need for fertilizer K (Fig. 5). The monitoring of changes in K balances and fertilizer K needs arising from the adoption of water-saving technologies in areas with high use of tube-well water rich in K is merited.

Potassium deficiencies in the rice–wheat system are more likely in areas with little K input from irrigation water and limited retention of crop residues. Although K is high in irrigation water from tube wells in the northwestern IGP (Pasricha et al. 2001), irrigation water can be lower in K in other rice–wheat areas of the IGP. Analysis of 21 samples of irrigation water from tube wells in rice–wheat areas of Uttaranchal, India, for example, revealed relatively low K concentration ranging from 0.8 to 2.8 mg L^{-1}, with a median of 1.3 mg L^{-1} (unpublished data, IRRI Reversing Trends in Declining Productivity project, 1997–2000). At these K concentrations, the K input from irrigation water for a rice–wheat cropping cycle would approximate 25 kg ha^{-1}, leading to markedly negative K balances regardless of residue retention (Fig. 5).

The rice–maize cropping system, because of the high yields of hybrid maize, can be a large net exporter of K and P (Fig. 7). The conversion of rice–rice or rice–wheat to rice–maize cropping could lead to a rapid depletion of soil K and P if K and P fertilizer are not appropriately adjusted to account for the higher crop production and plant accumulation of nutrients. Guidelines for determining field-specific K and P requirements that optimally balance the trade-offs between short-term profitability and longer-term sustainable productivity can therefore be especially important for the emerging high-yielding rice–maize system. Based on K balances, fertilizer K needs could be particularly high when maize residue is not retained in the field either because of off-field value such as for fodder or because it is a nuisance during subsequent tillage and establishment practices for rice (Fig. 8b).

Determination of fertilizer K and P rates

The established RIE for K and P for a crop (i.e., 2.7 kg P and 15.9 kg K per tonne of grain for rice, Table 3) can be used to determine fertilizer P and K requirements that are based on a targeted attainable yield, nutrient balances, and anticipated yield gain from the added nutrient. When yield gain from an added nutrient is small or negligible, the application of nutrient would not be recommended with solely a yield gain approach (equations 7 and 8), but the failure to apply any nutrient could result in rapid nutrient depletion, especially at high yields (Fig. 10 bd). A nutrient maintenance approach based on nutrient balances, on the other hand, would recommend application of nutrient even when yield gain is not certain.

Use of a full maintenance approach (equations 9 and 10) as advocated by Witt and Dobermann (2004) and Witt et al. (2007) for rice can result in relatively large applications of the nutrient, which would be unprofitable in the absence of a yield gain from the added nutrient. A partial maintenance approach, rather than a full maintenance approach, for determining fertilizer requirements can include an estimate of nutrient supply as affected by soil processes and soil characteristics and provide an option to balance the trade-offs between longer-term sustained productivity and short-term profitability.

The merit of a partial maintenance approach for determining fertilizer K requirements can be illustrated with results from a long-term fertilizer experiment with two rice crops per year in West Java, Indonesia (Abdulrachman et al. 2006). The yield loss from not applying fertilizer K during the initial five years (10 crops) was not statistically significant or certain to farmers in any season. Use of a yield gain approach in such a situation would result in no use of fertilizer K. Yet, the cumulative yield loss without fertilizer K for the 10 crops was 3 t ha^{-1} or 0.3 t ha^{-1} crop^{-1}. Use of a full maintenance approach would result in mean application of about 30 kg K ha^{-1} for each crop, which could be financially unattractive with probable farm-gate prices for fertilizer and produced rice. Use of a lower fertilizer K rate based on an estimated sustainable extraction of K from soil reserves (i.e., partial maintenance using K_S in equation 13) and considering the farm-gate price of harvested rice relative to the farm-gate fertilizer price could help ensure a balance between short-term profitability and longer-term sustained productivity without a yield loss due to K deficiency.

We consequently recommend use of a partial maintenance approach for determining fertilizer K and P requirements when yield gain from an added nutrient is small or negligible. Based on the results of analyses in our study, we recommend a partial maintenance approach in which fertilizer rates are calculated to ensure that the depletion of the nutrient does not exceed a threshold limit (K_S and P_S) regardless of yield (equations 13 and 14). This avoids the risk of increasing nutrient depletion with increasing yield.

When a detectable yield gain from an added nutrient is certain, an approach other than solely maintenance or yield gain appears merited. Witt and Dobermann (2004) and Witt et al. (2007) combined full maintenance of soil fertility and yield gain approaches to determine fertilizer K and P requirements. They did not sum the fertilizer rates determined from full maintenance and yield gain approaches. Rather, they separately calculated fertilizer K or P rates with the two approaches and then selected the larger of the two calculated values as the fertilizer requirement. In this fashion the nutrient recommendation was never less than full maintenance and was potentially higher than full maintenance when yield gain from the added nutrient was appreciable.

The full maintenance plus yield gain approach of Witt and Dobermann (2004) and Witt et al. (2007) can result in a relatively large application of nutrient, which can potentially be unprofitable when farm-gate fertilizer prices are high relative to the farm-gate price of produced grain and crop response to the nutrient is modest. Based on the analyses in our study, we consequently recommend a partial maintenance plus yield gain approach to determine fertilizer requirements when the crop responds to the added nutrient. The calculated fertilizer requirement is the sum of the amount determined by partial maintenance and yield gain (equations 15 to 18 and equations 21 to 24). Calculated fertilizer requirements can result in positive nutrient balances, but the fertilizer rates can also result in slightly negative nutrient balances (Fig 12 bd and 13 bd) because maintenance is only partial. Our analysis highlighted the merit of expressing yield gain as a fraction of targeted yield rather than an absolute amount, because measured yield gains from fertilizer K and P across a wide range of yields approximate a fraction of the yield with full fertilization (Fig. 9).

The procedures and algorithms presented for determining fertilizer K and P requirements for rice can also be used for wheat and maize with appropriate RIEs determined by QUEFTS for the crops. The threshold limit for nutrient extraction from soil reserves (K_S and P_S) could differ between rice and wheat or maize because the release of soil nutrients can differ between saturated anaerobic soils in rice cultivation and aerobic soils in wheat and maize cultivation. Soil submergence in rice cultivation, for example, tends to increase P availability (Turner and Gilliam 1976), which might conceivably affect the limit of sustainable nutrient extraction from soil reserves as well as the yield gain of a crop from fertilizer P. For rice–wheat and rice–maize systems, this can influence the optimal distribution of fertilizer P between rice and the non-rice crop in the rotation (Gill and Meelu 1983).

Conclusions

Fertilizer K and P requirements for a specific field can be determined with an SSNM-based approach using attainable target yield, nutrient balances, and probable yield gains from added nutrient. One standardized RIE value per nutrient for a crop facilitates the determination of nutrient balances in the algorithms. The partial maintenance and partial maintenance plus yield gain approaches that we have presented can be used in computer-based decision tools such as Nutrient Manager for Rice (IRRI 2010), which is designed to quickly provide extension workers, crop advisors, and farmers with fertilizer best management practices for specific rice fields. Each decision tool consists of questions readily answered within 15 minutes without the need for soil analysis. The responses to the questions provide sufficient information to develop field-specific fertilizer K and P recommendations using approaches and algorithms we have described in this paper. The generic SSNM-based principles and algorithms we presented for K and P are well suited for the rapid development and extension of field-specific fertilizer recommendations for rice, and they can be readily adapted for use with wheat and maize.

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References

Abdulrachman S, Witt C, Buresh RJ (2006) The need for potassium fertilization in rice and experiences from a long-term experiment in Indonesia. e-ifc no. 10, International Potash Institute. www.ipipotash.org/eifc/2006/10/6. Accessed 25 January 2010

Alam MM, Ladha JK, Khan SR, Foyjunnessa, Rashid H, Khan AH, Buresh RJ (2005) Leaf color chart for managing nitrogen fertilizer in lowland rice in Bangladesh. Agron J 97: 949–959

Ali MY, Waddington SR, Hodson D, Timsina J, Dixon J (2008) Maize-rice cropping systems in Bangladesh: Status and research opportunities. International Maize and Wheat Improvement Center (CIMMYT), Mexico, D.F.

Bijay-Singh, Yadvinder-Singh, Imas P, Jing-chang X (2004) Potassium nutrition of the rice–wheat cropping system. Adv Agron 81: 203–259

Bouman BAM, Humphreys E, Tuong TP, Barker R (2006) Rice and water. Adv Agron 92: 187–237

Bouman BAM, Tuong TP (2001) Field water management to save water and increase productivity in irrigated rice. Agric Water Manage 49: 11–30

Buresh RJ, Reddy KR, van Kessel C (2008) Nitrogen transformations in submerged soils. In: Schepers JS, Raun WR (ed) Nitrogen in agricultural systems. Agronomy Monograph 49. ASA, CSSA, and SSSA, Madison, WI, USA, pp 401–436

Buresh RJ, Witt C (2007) Site specific nutrient management. Proceedings of the IFA international workshop on fertilizer best management practices, 7–9 March 2007, Brussels, Belgium. International Fertilizer Industry Association, Paris, pp 47–55.

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

Dobermann A, Fairhurst T (2000) Rice: Nutrient disorders and nutrient management. Potash and Phosphate Institute (PPI) and Potash and Phosphate Institute of Canada (PPIC), Singapore and International Rice Research Institute (IRRI), Los Baños, Philippines

Dobermann A, Witt C, Dawe D (eds) (2004) Increasing the productivity of intensive rice systems through site-specific nutrient management. Science Publishers Inc., Enfield, NH, USA and International Rice Research Institute (IRRI), Metro Manila, Philippines

Dobermann A, Witt C, Dawe D, Abdulrachman S, Gines GC, Nagarajan R, Satawathananont S, Son TT, Tan PS, Wang GH, Chien NV, Thoa VTK, Phung CV, Stalin P, Muthukrishnan P, Ravi V, Babu M, Chatuporn S, Sookthongsa J, Sun Q, Fu R, Simbahan GC, Adviento MAA (2002) Site-specific nutrient management for intensive rice cropping systems in Asia. Field Crops Res 74: 37–66

Erenstein O (2009) Comparing water management in rice–wheat production systems in Haryana, India and Punjab, Pakistan. Agric Water Manage 96: 1799–1806

Gill HS, Meelu OP (1983) Studies on the utilization of phosphorus and causes for its differential response in rice–wheat rotation. Plant Soil 74: 211–222

Gupta RK, Yadvinder-Singh, Ladha JK, Bijay-Singh, Singh J, Singh G, Pathak H (2007) Yield and phosphorus transformations in a rice–wheat system with crop residue and phosphorus management. Soil Sci Soc Am J 71: 1500–1507

Haefele SM (2001) Improved and sustainable nutrient management for irrigated rice-based cropping systems in West Africa. PhD dissertation. Hamburg University, Germany.

Haefele SM, Wopereis MCS, Ndiaye MK, Barro SE, Ould Isselmou M (2003) Internal nutrient efficiencies, fertilizer recovery rates and indigenous nutrient supply of irrigated lowland rice in Sahelian West Africa. Field Crops Res 80: 19–32

IRRI (International Rice Research Institute) (2010) Nutrient management decision tools. www.irri.org/nmrice. Accessed 10 May 2010

Khurana HS, Phillips SB, Bijay-Singh, Alley MM, Dobermann A, Sidhu AS, Yadvinder-Singh, Peng S (2008) Agronomic and economic evaluation of site-specific nutrient management for irrigated wheat in northwest India. Nutr Cycl Agroecosyst 82: 15–31

Janssen BH, Guiking FCT, Van der Eijk D, Smaling EMA, Wolf J, van Reuler H (1990) A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46: 299–318

Ladha JK, Kumar V, Alam MM, Sharma S, Gathala MK, Chandna P, Saharawat YS, Balasubramanian V (2009) Integrating crop and resource management technologies for enhanced productivity, profitability, and sustainability of the rice-wheat system in South Asia. In: Ladha JK et al. (eds) Integrated crop and resource management in the rice–wheat system of South Asia. International Rice Research Institute (IRRI), Metro Manila, Philippines

Liu M, Yu Z, Liu Y, Konijn NT (2006) Fertilizer requirements for wheat and maize in China: the QUEFTS approach. Nutr Cycl Agroecosyst 74: 245–258

Lorenz N, Verdell K, Ramsier C, Dick RP (2009) A rapid assay to estimate soil microbial biomass potassium in agricultural soils. Soil Sci Soc Am J 74: 512-516

Maclean JL, Dawe DC, Hardy B, Hettel GP (2002) Rice almanac: Source book for the most important activity on earth. Third edition. CABI Publishing, Wallingford, UK and International Rice Research Institute (IRRI), Metro Manila, Philippines

Mamaril CP, Castillo MB, Sebastian LS (2009) Facts and myths about organic fertilizers. Philippine Rice Research Institute (PhilRice), Science City of Muñoz, Nueva Ecija, Philippines

Mandal KG, Misra AK, Hati KM, Bandyopadhyay KK, Ghosh PK, Mohanty M (2004) Rice residue-management options and effects on soil properties and crop productivity. J Food Agric Environ 2: 224–231

Mukhopadhyay D, Majumdar K, Pati R, Mandal MK (2008) Response of rainfed rice to soil test-based nutrient application in Terai alluvial soils. Better Crops Plant Food 92 (4): 13–15

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

Naklang K, Harnpichitvitaya D, Amarante ST, Wade LJ, Haefele SM (2006) Internal efficiency, nutrient uptake, and the relation to field water resources in rainfed lowland rice of northeast Thailand. Plant Soil 286: 193–208

Pasricha NS, Sharma BD, Arora CL, Sidhu PS (2001) Potassium distribution in soils and ground waters of Punjab. J Potassium Res 17: 1–13

Pathak H, Aggarwal PK, Roetter R, Kalra N, Bandyopadhaya SK, Prasad S, Van Keulen H (2003) Modelling the quantitative evaluation of soil nutrient supply, nutrient use efficiency, and fertilizer requirements of wheat in India. Nutr Cycl Agroecosyst 65: 105–113

Saleque MA, Anisuzzaman M, Moslehuddin AZM (2009) Quantity-intensity relationships and potassium buffering capacity of four Ganges River floodplain soils. Comm Soil Sci Plant Anal 40: 1333–1349

Setiyono TD, Walters DT, Cassman KG, Witt C, Dobermann A (2010) Estimating the nutrient uptake requirements of maize. Field Crops Res (under review)

Sharma PK, De Datta SK (1986) Puddling influence on soil, rice development, and yield. Soil Sci Soc Am J 49: 1451–1457

Slaton NA, Golden BR, Norman RJ, Wilson CE, DeLong RE (2009) Correlation and calibration of soil potassium availability with rice yield and nutritional status. Soil Sci Soc Am J 73: 1192–1201

Singh M, Singh VP, Reddy DD (2002) Potassium balance and release kinetics under continuous rice–wheat cropping system in Vertisol. Field Crops Res 77: 81–91

Turner BL, Haygarth PM (2001) Phosphorus solubilization in rewetted soils. Nature 411:258

Turner FT, Gilliam JW (1976) Increased P diffusion as an explanation of increased P availability in flooded rice soils. Plant Soil 45: 365–377

Witt C, Buresh RJ, Peng S, Balasubramanian V, Dobermann A (2007) Nutrient management. In: Fairhurst et al. (ed) Rice: A practical guide to nutrient management. International Rice Research Institute (IRRI), Los Baños, Philippines and International Plant Nutrition Institute and International Potash Institute, Singapore, pp 1–45

Witt C, Dobermann A (2004) Toward a decision support system for site-specific nutrient management In: Dobermann A, Witt C, Dawe D (ed) Increasing productivity of intensive rice systems through site-specific nutrient management. Science, Enfield, NH, USA and International Rice Research Institute (IRRI), Metro Manila, Philippines, pp 359–395

Witt C, Dobermann A, Abdulrachman, S, Gines HC, Wang G, Nagarajan R, Satawatananont S, Son TT, Tan PS, Tiem LV, Simbahan GC, Olk DC (1999) Internal nutrient efficiencies of irrigated lowland rice in tropical and subtropical Asia. Field Crops Res 63: 113–138

Witt C, Pasuquin JMCA, Pampolino MF, Buresh RJ, Dobermann A (2009) A manual for the development and participatory evaluation of site-specfic nutrient management for maize in tropical, favorable environments. International Plant Nutrition Institute, Penang, Malaysia

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Site specific potassium management in rice based cropping systems in India

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Abstract Potassium fertility of Indian soils has been on the decline as is evident from comparative soil test results over the years and increasing response to potassium application in different crops and soils. Several experimental evidences showed that potassium balances in rice-based cropping systems are essentially negative due to deficit application rates of the nutrient compared to its uptake. This has lead to considerable K mining from soils that is undesirable for long term sustainability of rice-based systems. Potassium dynamics in soils are governed by the mineralogy, while the K–supplying capacity of the soils depends on the nature of the K-bearing minerals and the extent of weathering. Variability in type and state of weathering of the K-bearing minerals as well as difference in management history leads to spatial difference in K fertility of soils. The current practice of applying potassium at a blanket dose without taking into account such variability is thus limiting crop yield and causing K mining as was evident from long-term experiments. The concept of site-specific potassium management in rice-based cropping systems on the other hand provides an approach that takes into account the K supplying capacity of soils and K requirement of crops while formulating potassium recommendations. Experimental evidences showed that such an approach can improve yield and economics of production of rice-based cropping systems and can reverse the current negative yield trends.

Keywords potassium imbalance in Indian agriculture • soil mineralogy and potassium availability • site specific potassium management • rice based cropping systems

Introduction

Potassium (K) did not receive much attention in India till the '80s because of the general belief that the Indian soils were well supplied with potassium (Pasricha

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and Bansal 2001). However, the picture of crop responses to potassium in India has been changing with time. Indeed, there is a growing evidence of increasing deficiency of K as a result of imbalanced use of nitrogen (N) or N and phosphorus (P). Even under the so-called optimum rates of NPK application in long-term experiments, the K balance under most of the soil-cropping systems was negative (Subba-Rao et al. 2001). Such imbalance in potassium application, however, has variable impact on crop production due to the fact that K-supplying capacities of soils vary based on mineralogy and dynamics of a particular soil type. So the current practice of applying potassium at a blanket dose without taking into account the soil concerned is either limiting crop yield and causing K mining (deficit K application) or wasting resource that are entirely imported (excess application). Attaining Food Security had been a major challenge for the nation since independence. The current stagnation in food grain production necessitates special initiatives to meet the increasing demands of food grains. Expansion of the area sown to rice, and crops grown in sequence to it, has ceased to be a major source of increased output. Most of the targeted increase in production must now result from greater yield per hectare. Appropriate nutrient management in general and potassium management in particular, will play a major role in overcoming stagnation in food grain production. Future strategies for potassium management need to be more site-specific and dynamic based on a quantitative understanding of the congruence between nutrient supply and crop demand. The current paper aims at analyzing the role of site-specific potassium management in improving productivity of rice-based cropping sequences.

Potassium scenario in India

Potassium (K) has long been a neglected nutrient in Indian agriculture. Analysis of the fertilizer consumption scenario over the past decades shows that potash contributed to less that 10% of the total nutrient consumption in the country. Removal of K in proportion to N is very high in cropping systems, particularly those involving cereal and fodder crops (Yadav et al. 1998) (Table 1). Potassium requirements of crops are in general identical to N and 3-5 times higher than P. However, average K use in India over the last 30 years has been about one-seventh of N and about one-third of P.

An illustrative balance-sheet of NPK in Indian agriculture (Table 2) shows an annual depletion of K_2O to the tune of 10.20 Mt and 5.97 Mt on gross and net basis, respectively (Tandon 2004). Of the current net negative NPK balance or annual depletion of 9.7 Mt, 19% is N, 12% P and 69% K. Such alarming contribution of K towards the negative balance of NPK is a major concern.

Consequence of such imbalanced K application is evident in the information based on analysis of more than 11 million soil samples that reflect the changing K fertility status of soils in different parts of the country (Hasan 2002). The distribution of districts considered low, medium, and high in K fertility show that out of 371 districts, for which information is available, the respective number of districts characterized as low, medium, and high are 76, 190, and 105. Thus, 21% of the districts are low, 51% are medium, and 28% are high, using the nutrient index values suggested by Ramamurthy and Bajaj (1969). Comparing these results with those presented earlier by Ghosh and Hasan (1980), the low and high categories have decreased by 0.6 and 6.4%, respectively, while the medium category increased by 7**%.** All this indicates that K fertilizers were scantily applied in the last two decades as the low category has virtually remained the same and the high area has fallen.

Table 1 Nutrient uptake in important cropping systems

Crop sequence	Applied (kg ha^{-1})			Total yield (t ha^{-1})	Total uptake (kg ha^{-1})		
	N	P_2O_5	K_2O		N	P_2O_5	K_2O
Maize-Wheat-Green gram	260	70	50	8.2	306	27	232
Rice-Wheat-Green gram	260	70	50	11.1	328	30	305
Maize-wheat	250	54	75	7.6	247	37	243
Rice-Wheat	250	44	84	8.8	235	40	280
Maize-Wheat	240	52	100	7.7	220	38	206
Pigeon pea-Wheat	144	52	100	4.8	219	31	168
P. Millet-Wheat-Green gram	245	66	66	10.0	278	42	284
P. Millet-Wheat-Cowpea (Fodder)	245	66	66	19.5F	500	59	483
Soybean-Wheat	145	61	0	7.7	260	37	170
Maize-Wheat-Green gram	295	74	0	9.0	296	47	256
Maize-Rape-Wheat	330	69	0	8.6	250	41	200

Source: Yadav et al. 1998

Table 2 An illustrative nutrient balance sheet of Indian Agriculture

Nutrient	Gross balance sheet[#] (000 t)			Net balance sheet (000 t)		
	Addition	Removal	Balance	Addition	Removal	Balance
N	10,923	9,613	1,310	5,461	7,690	-2,229
P_2O_5	4,188	3,702	486	1,466	2,961	-1,493
K_2O	1,454	11,657	-10,202	1,018	6,994	-5,976
Total	16,565	24,971	-8,406	7,945	17,645	-9,701

[#] Gross balance is calculated on the basis of actual application while net balance is calculated by factoring in the efficiency of 50% for N, 35% for P_2O_5 and 70% for K_2O

Source: Tandon 2004

Rice-based cropping systems

Rice is the most important crop in India and plays a critical role in food security. More importantly, it is a choice crop of the millions of poor and small farmers not only for income but also for household food security. Intensification and diversification are two main trends of rice-based cropping systems as they have evolved in different agro-ecological regions in India where wheat, maize or one of many other secondary crops are grown during the part of the year when rice was not in the field. Diversification and intensification of rice-based systems was advocated to make a breakthrough in productivity and profitability, and several options with different levels of productivity and profitability were outlined by (Gill 2006; Gill et al. 2008). The most prevalent cropping systems are rice–rice, rice– rice–rice, rice–rice–pulse, rice–wheat, rice–oilseed crop, and more recently rice–maize. The rotation of rice-rice and rice-wheat, for example, are major agricultural production systems that account for 16 M ha of food grain producing area in India and are the mainstay of food security in the country.

However, the rice sector has witnessed rapid dynamism in production processes. After a four-fold increase in production during the past four decades, the production curves have started showing downward trend and productivity decelerating since the later half of the 1990s. The productivity decline is experienced not only in the core green revolution state of Punjab but also in several other states such as Tamilandu, Andhra Pradesh and Kerala, etc., including the rain-fed areas. There are several reasons for such stagnation, the most conspicuous being wide-scale nutrient depletion through crop harvest, on one hand and low level of replenishment through inadequate nutrient supply, on the other.

Tiwari et al. (2006) in their multi-location trial with rice-wheat system showed that the average system uptake (rice + wheat) of nutrients over 10 sites and 2 years was 761 kg of $N + P_2O_5 + K_2O$ ha^{-1} $year^{-1}$ for an average system yield of 13 t ha^{-1}. The mean uptake of $N: P_2O_5:K_2O$ was in the proportion of 100:29:129. Similar experiments with rice-rice system across 6 sites and 2 years showed average uptake of 782 kg of $N + P_2O_5 + K_2O$ for an average system yield of 12 t ha^{-1} with an average uptake ratio of 100:40:133 for $N:P_2O_5:K_2O$. The mean K uptake was 1.74 times the K input in case of rice-wheat system, while mean uptake was 62% higher than K input in rice-rice system suggesting net depletion of soil K in all the sites. The K-omission plots (no external K application) in this study showed that native potassium supply in rice-wheat system varied from 205 to 354 kg K_2O ha^{-1} $year^{-1}$ depending on location. In treatments based on K supply exclusively from native sources (K-omission plots), the yield levels supported by sites differed considerably. Thus, Ranchi with a native supply of 205 kg K_2O ha^{-1} $year^{-1}$ produced 65% lesser system yield (rice-wheat) than did Ludhiana which provided 354 kg K_2O ha^{-1} $year^{-1}$ in absence of external supply (Tiwari et al., 2006). Similar results were obtained in rice-rice cropping system by the authors. This suggests that site-specific potassium application, based on estimation of soil supply and crop requirement, will be required to support equal levels of yields in rice-based cropping systems in different locations.

Mineralogy and K availability

Potassium availability to plants is regulated in soils by the soluble, exchangeable and non-exchangeable fractions of K that are interrelated by a dynamic equilibrium. The driving force for this equilibrium is largely a function of clay composition, while the magnitude of the process is a function of clay content of soil. As growing season is limited in most cases, a high growth rate for high yield can only be maintained with high flux rates of nutrients to the plant roots. Therefore, mineralogy plays a pivotal role in potassium supplying capacity of a particular soil (Rao and Rao 1996). The mineral sources of K in soils are the dioctahedral micas: muscovite, glauconite, and hydrous mica or illite; the trioctahedral mica, namely biotite and phlogopite and the feldspar, namely sanidine, orthoclase and microlone (Sarma 1976). Weathering of micas / feldspars leads to the formation of secondary minerals (such as smectite or vermiculites), *via* intermediates like illites, with simultaneous release of K (Sparks and Huang 1985). Results of numerous studies (Sanyal et al. 2009) suggest that for soils of low intensity of weathering and from trioctahedral mica parent material, K release to soil solution is rather high as for the crop need and the replenishment of the exhausted K in soil due to crop removal. For soils of dioctahedral mica parent material, and a moderate state of weathering or both, K release is less, but it is the least for soils of low mica content or intensive weathering, or both. Indeed, while formulating a sound K fertilizer recommendation, it is imperative that the above characteristics need to be taken into account.

Plant uptake of K is related to the weathering of feldspars and micas in soil environments. Micas are more important than K-feldspars in supplying K to plants (Rich 1972). The native K status depends, not only on the parent material of soil, but also on the subsequent stages of weathering of the parent material. So the weathering history of a mineral phase, rather than its mere presence, may be an important factor to be reckoned while relating the plant availability of soil K to the soil mineralogy (Sanyal and Majumdar 2001). An example of such postulate is provided by a sharp contrast between the Entisol and the Alfisol under rice-based cropping sequence in West Bengal (Table 3) where despite having almost the same amount of illite content, there was a wide variation in total K and nonexchangeable K (NEK) contents of these soils (Sanyal et al. 2009). This obviously is linked to the relative stages of weathering of the illitic mineral phase in the given soils (Sanyal et al. 2009; Ghosh and Sanyal 2006). Such observations have important bearing to the fertilizer K recommendations to support the different cropping sequences.

Recently, Chatterjee (2008) found wide variability in soil K fractions in selected rice growing soils in the alluvial tract of West Bengal. Descriptive statistics of K fractions in soils of three adjacent blocks of Nadia district showed wide variability (Table 4). The water soluble and exchangeable form of potassium

Table 3 Distribution of different clays and forms of K in two soils of West Bengal

Soil properties		Kalyani (an Entisol)	Anandapur (an Alfisol)
Illite	(%)	38.0	38.8
Smectite	(%)	28.0	-
Kaolinite	(%)	11.0	61.2
Chlorite	(%)	6.0	-
Vermiculite	(%)	17.0	-
Nonexchangeable K (NEK)	cmol (p^+) kg^{-1}	6.0	0.6
Total K	cmol (p^+) kg^{-1}	52.2	29.0

Source: Sanyal et al. 2009; Ghosh and Sanyal 2006

varied to a greater extent (33.96 % and 52.87% respectively) than did the non-exchangeable form of potassium (20.12%) (Table 4).

Table 4 Variability of different forms [cmol (p^+) kg^{-1}] of potassium in the three study areas

Statistical parameters	Water soluble K	Exchangeable K	Available K	Nonexchangeable K
Minimum	0.020	0.017	0.093	2.83
Maximum	0.066	0.329	0.350	6.07
Mean	0.042	0.121	0.163	4.15
Standard Deviation	0.014	0.064	0.056	0.83
CV (%)	33.96	52.87	34.39	20.12

Source: Chatterjee 2008

Recent studies on potassium variability (IPNI 2006-07) in the alluvial and red and lateritic soil zones of West Bengal and Jharkhand showed that variability of available potassium in soils is quite high among fields within villages (Table 5). Such short-range variability was attributed to several factors including fertilization and cropping history as well as resource availability to the farmers (Sen and Majumdar 2006; Sen et al. 2008).

These experimental observations suggest that due consideration must be given to the nature and composition of soil minerals while formulating a K fertilization strategy in rice based systems and any attempt to develop a “one fits all” strategy will fail to produce the desired improvement in productivity and profitability, while it will encourage nutrient depletion.

Table 5 Variability of available potassium (kg ha^{-1}) among farmers' plots within a village

Location	Maximum	Minimum	Mean	Standard Deviation	CV (%)
Ghoragacha, Nadia, West Bengal	640	96	283	109	39
Sripurdanga, Murshidabad, West Bengal	448	87	254	93	37
Bahadurpur, Birbhum, West Bengal	150	96	110	9	8
Meherpur, Birbhum, West Bengal	494	24	168	113	68
Barhu Simatoli, Ranchi, Jharkhand	356	61	142	71	50

Source: IPNI 2006-07

Changes in potassium fertility in rice-based cropping systems

Depletion of soil K reserves under continuous rice-based system has become a matter of concern. Tiwari (1985) observed a decline in available K by 17% and 28% after two crop cycles in the middle Indo-Gangetic plains. Sekhon (1999), studying K depletions in the soils of Indo-Gangetic plains (IGP), showed that six out of eight benchmark soils studied showed considerable decrease in ammonium acetate and nitric acid soluble K-fractions (denoting the exchangeable and non-exchangeable K fractions, respectively) after 10 years of continuous cultivation (Table 6).

Table 6 Changes observed in soil fertility in some soil series supporting rice-based cropping system in the Indo-Gangetic Plains

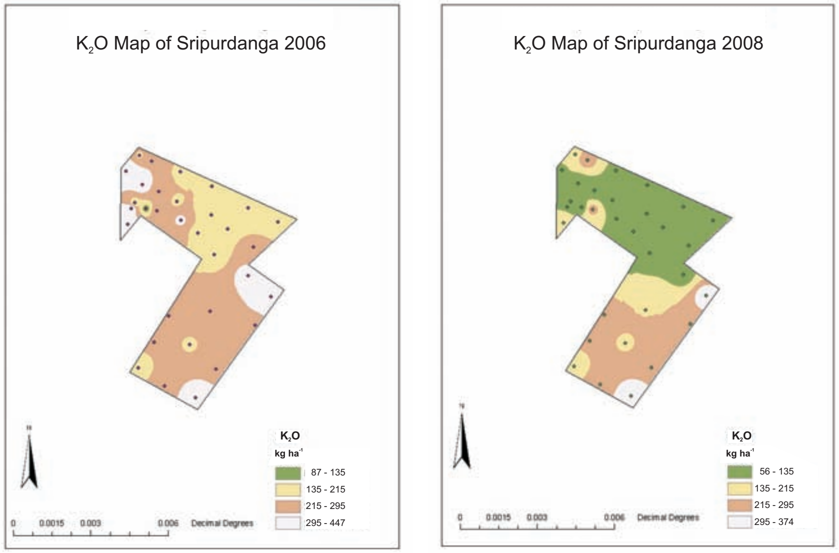
Soil Series and Location	NH_4OAc-K (mg kg^{-1})		HNO_3-K (mg kg^{-1})	
	First sampling	After 10 years	First sampling	After 10 years
Nabha, Punjab	104±54	63±41	965±25	875±23
Akbarpur, UP	125±41	71±23	1448±20	1231±18
Rarha, UP	95±33	79±20	1531±35	1497±18
Hanrgram, WB	132±53	93±16	425±16	400±19
Kharbona, WB	42±17	29±16	119±34	109±26

Source: Sekhon 1999

Decrease in available potassium content of soils, even where K was applied in both rice and wheat, was observed in long-term experiments progressing at different locations in IGP (Yadav et al. 2000a). The long-term experiments also revealed that response to applied potassium increased steadily over the last 20 years as a result of depletion of soil K (Swarup and Srinivasa Rao 1999). Singh et al. (2002) in a 8 year rice-wheat cropping system experiment observed that application of K at 33 kg ha^{-1} to both the crops caused a negative potassium balance of 103 to 156 kg ha^{-1} year^{-1} depending on the rate of N application. Such changes in K fertility under intensive cropping, however, can also be quite abrupt, particularly when vegetables are included in the rice-based system. Sen et al. (2008), while assessing changes in nutrient availability through GIS-based fertility mapping, found that K fertility in an intensively cultivated village in the alluvial zone of West Bengal decreased perceptibly within two years. For available K_2O, the range changed from 87-448 kg ha^{-1} in 2006 to 56-375 kg ha^{-1} in 2008 and the mean from 166 kg ha^{-1} in 2006 to 88 kg ha^{-1} in 2008. Potassium fertility of the village was generally low to medium in 2006 but the frequency distribution shifted more towards the low fertility category with a substantial increase in sample number in the lowest category (Figure 1). The authors found that lower application of potassium during this period due to unavailability and high uptake of K by the vegetable crops contributed to this swift decline in K fertility of the soils.

Consequence of such depletion scenario across the country has led to negative potassium balance in most cropping systems, including rice-based systems. Ladha et al. (2003) analyzed yield trends in rice-wheat systems in the IGP, non-IGP areas of India and China and noted that rice and wheat yields stagnated at 72 and 85% of long-term experiments where recommended rates of NPK were applied. These authors further reported that fertilizer K rates used were not sufficient to sustain a neutral K input-output balance in 90% of the long-term experiments, while all the experiments with significant yield decline had large negative K balances. It is clear that such negative K balances in soils will adversely affect the sustainability of rice-based systems and a rational approach of K management, keeping in mind the variable soil supplying power and nutrient requirements of crops/cropping systems, will be necessary to reverse the trend.

Fig. 1 Comparative maps of available potassium before and after four cropping seasons



Site-specific potassium management

The basic principle of maintaining the fertility status of a soil under high intensity crop production systems is to annually replenish those nutrients that are removed from the field. Site specific nutrient management (SSNM) provides an approach of nutrient management that takes into account 1) nutrient requirement for unit yield, 2) nutrient contribution from soils, and 3) nutrient contributions required from fertilizers to formulate fertilizer recommendation. Nutrient use on the principles of SSNM could provide an avenue to reverse the declining productivity trend and nutrient mining from soils.

Undoubtedly, rice based cereal cropping systems are very exhaustive and require high quantum of macro, secondary and micronutrients. They are practiced in a myriad of soil conditions in IGP and non-IGP areas. Variability in nutrient reserves, nutrient supplying capacity of the soils under these vastly different soil and climatic conditions and management strategies require that potassium is applied in a site-specific manner to improve productivity and maintain soil fertility.

It is well established that crop yields, profit, plant nutrient uptake and nutrient use efficiencies can be significantly increased by applying fertilizers on a field specific and crop season specific manner (Bijay-Singh et al. 2003). Fertilizer K rates predicted by the QUEFTS model (Janssen et al. 1990) to achieve high yield and maintain soil fertility are usually higher than the rates currently applied by farmers. Potassium rates in SSNM plots ranged from 50 to 66 kg ha^{-1} crop^{-1} while the average farmer fertilizer K rate was 30 kg ha^{-1} (Bijay-Singh et al. 2003).

The findings from a survey conducted by the Project Directorate for Cropping Systems Research (ICAR), India on the use pattern of nutrients to rice-wheat system in various sub-regions of the Indo-Gangetic Plains are presented in Table 7. The economic, social and climatic factors as well as soil and institutional factors were largely responsible for spatial variation in major nutrients application. The most conspicuous point to note was the use of potassium in a much imbalanced manner in both the crops that seems to be the prime factor causing yield stagnation of rice-wheat system in IGP.

Table 7 Major nutrients use in various sub regions of the Indo-Gangetic Plains

Sub region of IGP	Area (X 10^3 ha)	Nutrient use (kg ha^{-1})					
		N		P		K	
		Rice	Wheat	Rice	Wheat	Rice	Wheat
Trans-Gangetic Plains	3809	166.1	154.2	51.3	49.6	0.8	12.3
Upper-Gangetic Plains	3160	115.0	109.8	40.7	37.6	5.2	11.4
Mid-Gangetic Plains	3133	116.1	100.0	29.1	32.7	4.3	20.5
Lower-Gangetic Plains	119	82.6	87.1	16.3	21.4	36.4	44.0

Adapted from Sharma (2003) after modification

Recent work on site-specific potassium management (SSKM) by Chatterjee and Sanyal (2007) across three locations and twelve sites in the alluvial soils of West Bengal showed significant yield increase in the SSKM plot over the general recommendation. The K application rate of the SSKM plots were based on available and non-exchangeable K contents in each site as well as the yield target. The SSKM plot registered higher K uptake than that for the general recommendation and farmers' practice, the highest mean residual crop available potassium in the soil and highest relative agronomic efficiency among the treatments. Tiwari et al. (2006) working in 17 locations on rice-rice and rice-wheat systems also showed that economically optimum potassium rates varied according to locations (Table 8).

Potassium application in site-specific manner significantly enhanced the rice-wheat system productivity in the above study. The system yield increase was associated with response rate of 8.9 kg grain kg^{-1} K$_2$O applied with a Benefit: Cost Ratio (BCR) of 4.3 to 13.5 depending on the location. Pooled data of location and K rates showed that benefit for K application were 5 or more in 81% cases and 10 or more in 57% cases. In rice-rice system, the response to K application was 5 kg grain kg^{-1} K$_2$O. Across the sites, the BCR for K application was 5 or higher in 59% cases. The authors concluded that optimum potash application can increase the productivity of the rice-rice system by 1300-1900 kg ha^{-1} and the current general K application rates need upward revision to achieve higher target yields. Gill et al. (2009) studied the level of response of NPK in major cropping systems across 32 centers located in different agro-climatic zones. The response to potassium in rice based cropping systems varied from 11.7 to 51.0 kg rice grain equivalent kg^{-1} nutrient. The oilseeds crops following rice gave response of 17.3 to 24.6 kg rice grain equivalent kg^{-1} nutrient, while in rice based cereal cropping systems, the potassium response was confined to the range of 14.0 to 16.2 kg rice grain equivalent kg ha^{-1} nutrient (Table 9).

Table 8 Economically optimum potassium rates in rice-wheat and rice-rice systems (mean of two years)

Location	Optimum rates (kg K$_2$O ha^{-1})			Location	Optimum rates (kg K$_2$O ha^{-1})		
	Rice	Wheat	System		Rice	Rice	System
Sabour	75	76	153	Maruteru	93	94	188
Palampur	76	103	182	Jorhat	89	92	176
R. S. Pura	94	104	196	Navsari	72	106	186
Ranchi	82	91	179	Karjat	94	95	165
Ludhiana	102	84	188	Coimbatore	34	45	72
Faizabad	80	60	143	Thanjavur	86	82	178
Kanpur	89	66	153				
Modipuram	87	88	177				
Varanasi	85	104	171				
Pantnagar	76	77	148				

Source: Tiwari et al. 2006

The reasonably high response to potassium of rice based cropping system is thus worth noting and application of K seems a necessity for ensuring high grain yield realization. The highest response to potassium was found in rice-tomato cropping systems where the response was up to 51 kg rice grain equivalent kg^{-1} potassium. The economic response to potassium in cereal based cropping system varied from Rs. 9.4 to 10.6 Rupee^{-1} invested. The rice followed by oilseed gave economic response in the range of Rs. 5.0 to 17.6 Rupee^{-1} invested. While in rice-chickpea, the economic response was Rs. 8.3 Rupee^{-1} invested. The highest economic response was recorded in rice-tomato (Rs. 24.9 Rupee^{-1} invested), thereby clearly advocating the use of potassium as per the recommended dose (Gill et al. 2009).

Recently Mukhopadhyay et al. (2008), while studying a rice-rice system in the Terai alluvium, found that omitting potassium from a soil test based

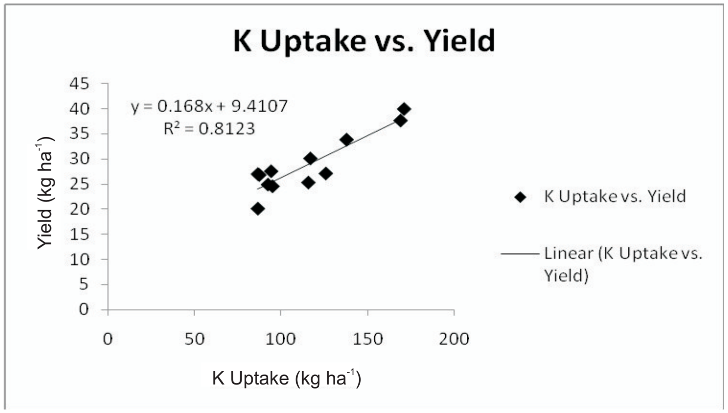
Table 9 On-farm response to nutrient in rice based cropping system

Cropping system	Response (kg rice grain equivalent kg^{-1} nutrient)			Economic response (Rs. Rs.$^{-1}$ invested on nutrient)		
	N	P$_2$O$_5$	K$_2$O	N	P$_2$O$_5$	K$_2$O
Rice-rice	12.0	14.6	16.2	9.9	5.1	10.6
Rice-wheat	10.1	15.9	14.0	8.4	5.7	9.4
Rice-groundnut	14.3	22.8	24.6	11.8	8.1	17.6
Rice-chickpea	14.0	11.7	11.7	11.4	4.1	8.3
Rice-mustard	10.8	19.5	17.3	8.4	6.4	5.0
Rice-tomato	19.5	20.2	51.0	10.3	5.1	24.9

Source: Gill et al. 2009

recommendation caused a yield loss of 20-32%. They found highly positive correlation between yield and potassium uptake (Figure 2) that corroborated the importance of soil test based potassium application in rain-fed rice systems.

Fig. 2 Interrelation between grain yield and uptake of potassium in rice (IET 1444)



Source: Mukhopadhyay et al. 2008

Potassium based nutrient management tested at cultivators' field under the All India Coordinated Research Project (AICRP) on Cropping System (2006-07) had highlighted the response of potassium and sulphur in rice-wheat system. The average nutrient management options under the existing farmers' crop management practice (FCM) gave 4.32 to 6.95 t ha^{-1} paddy yield, which improved by 3 to 25% with recommended management practice at different locations. Inclusion of K, S and Zn, along with farmers' management, produced extra yield of 0.75 to 1.78 t ha^{-1} depending on locations. The corresponding response to potassium over N P clearly demonstrated the major role of potassium towards enhancement in yield (Table 10). Wheat productivity increased from 0.13 to 0.68 t ha^{-1} over farmers' fertilizer management practice (FFP), along with the corresponding response to potassium application being 0.13 to 0.68 t ha^{-1} over NP, thereby stressing the fact that yield and response to potassium are variable and K must be applied in a site-specific manner to improve productivity of rice based systems.

Spatial variability and GIS mapping: A key to future

Thus, the question that arises now is where one goes from such concepts like targeted yield, soil test recommendation, and SSNM for efficient and balanced use

Table 10 Grain yield response (t ha^{-1}) to K, S and Zn application over farmers' fertilizer management practice in rice-wheat system

Nutrient applied	Modi-puram	Fatehgarh Sahib	Sabour	Pantnagar	Varanasi	Banda
	Rice (t ha^{-1})					
K over NP	0.47	0.40	0.76	0.66	0.47	0.79
K, S and Zn over NP	0.86	0.75	1.40	1.11	0.98	1.78
S and Zn over NP	0.30	0.47	0.57	0.26	0.30	1.01
S and Zn over NPK	0.40	0.35	0.63	0.45	0.50	0.99
	Wheat (t ha^{-1})					
K over NP	0.60	0.18	0.68	0.61	-	0.13
K, S and Zn over NP	0.85	0.34	1.20	0.92	-	0.50
S and Zn over NP	0.35	0.22	0.30	0.50	-	0.30
S and Zn over NPK	0.26	0.16	0.52	0.31	-	0.36

Source: Annual report of AICRP on Cropping Systems 2006-07

of plant nutrients. The SSNM requires intensive soil sampling and analyses in order to construct crop- and soil-specific nutrient recommendation. This provides a major challenge considering the fragmented land holdings in the country as well as the existing soil testing infrastructure. Geo-statistical analysis and GIS-based mapping effectively counters that challenge by providing an option to create soil fertility maps of large areas through interpolation of soil analysis data from a small number of samples (Sen et al. 2008). Such dynamic maps provide an opportunity to assess variability in distribution of native nutrients across a large area and thus aid in strategizing appropriate management of nutrients leading to better yield and environmental protection. Indeed, in India, where each farm family operates one or several small field plots, farmers' fertilizer decision making process is commonly limited by inadequate understanding of soil nutrient status or spatial nutrient variability of their plots, with such understanding on spatial variability of soil nutrients in fragmented land-holdings being expected to give a strong impact on the sustainable development of agriculture in the country. As mentioned earlier, Sanyal and Chatterjee (2007) revealed that contrast of non-exchangeable potassium and available potassium status between soils can be effectively utilized to modify the soil test-based fertilizer recommendation practices for potassium. Sen and Majumdar (2006) and Sen et al. (2008) documented wide spatial variability in available nutrient contents of soils even in small areas of intensively cultivated region of West Bengal. Such studies clearly highlighted the necessity to comprehensively understand the spatial variability of soil nutrients under the prevalent small-scale operation systems in India for developing the guidelines for soil nutrient management and fertilization for optimum production (Sen et al. 2008).

Conclusions

Larger proportion of mining in respect of potassium as mentioned in previous sections partly result from the average crop removal of 1.5 times more K than that of N and lower K application than N or P, with the misconception that the soils of the country are relatively rich in potash. Apart from this, relatively low cost per unit of nitrogen, its widespread availability, and quick and evident response of the plant has further accentuated such an imbalance. While it will be necessary to rationalize the use of N fertilizers, ominous signs are that if strategies and policies are not developed to boost K supplies, and this essential nutrient continues to remain neglected as in the past, future sustainability of rice-based systems is likely to be constrained mostly by K. Sustainability of the regions supporting high intensity cropping and fertilizer responsive strains are foreseen to be the earliest victims of such imbalance. Besides, our current understanding and interest on soil quality requires that enough focus is given towards the mining aspects of nutrients in general and potash in particular. As much as it may seem economically prudent to apply less potassium from external sources as it is an imported commodity, and rely more on the inherent potash supplying capacity of the soils, in the long-run it might turn out to be a very short-sighted approach as we lose the quality of a very vital resource of our country, our SOILS. Rather a balanced approach that takes into account soil properties, its potassium supplying capacity and potassium requirement of crops in the realm of site-specific nutrient management can reverse the declining production trend, improve the soil quality and thus will leave our environment clean for the posterity.

References

Annual Report (2006-07) All India Coordinated Research Project on Cropping System Research. Project Directorate for Cropping Systems Research, Modipuram, Meerut, Uttar Pradesh.

Bijay-Singh, Yadvinder Singh, Vashista M (2003) Potassium nutrition of rice-wheat cropping system in Indo-Gangetic Plains. Yadvinder-Singh, Bijay-Singh, Nayyar VK, Singh J (ed) Nutrient Management for Sustainable Rice-Wheat Cropping System. NATP, ICAR, New Delhi and PAU, Ludhiana, Punjab, pp 412

Chatterjee S (2008) Site specific potassium management with special emphasis on its dynamics for sustainable production in selected rice growing areas of West Bengal, Ph D Thesis, Bidhan Chandra Krishi Viswavidyalaya, Mohanpur, Nadia, West Bengal.

Chatterjee S, Sanyal SK (2007) Site-specific potassium management for rice grown in selected alluvial soils of West Bengal. Better Crops-India, 1:22-25.

Ghosh AB, Hasan R (1980) Soil fertility map of India, Indian Agricultural Research Institutes, New Delhi.

Ghosh S, Sanyal SK (2006) Final progress report of the Potash and Phosphate Institute of Canada-India Programme-funded project on phosphate and potash management to support rice-based cropping sequences in the lateritic and alluvial soils of West Bengal, Bidhan Chandra Krishi Viswavidyalaya, West Bengal

Gill MS (2006) Sustaining high yield of rice-wheat system through site specific nutrient management in Punjab. Indian J. Fertilizers 2:45-50

Gill MS, Gangwar B, Gangwar KS (2008) Site-specific crop management approach for high yield realization of cereal-based cropping systems. Indian J Fertilizers 4:31-34, 37-40, 43-46

Gill MS, Singh VK, Mahapatra IC (2009) Crop response to applied nutrient under different cropping systems. Paper presented in the brainstorming session on crop response and nutrient ratio, National Academy of Agricultural Sciences, New Delhi, pp 79-91

Hasan R (2002) Potassium status of soils of India. Better Crops International 16:3-5

International Plant Nutrition Institute (IPNI) 2006-07 Unpublished research reports, IPNI, Gurgaon, Haryana

Janssen BH, Guiking FCT, van der Eijk D, Smaling EMA, Wolf J, Van Reuler H (1990) A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). Geoderma 46:299-318

Ladha JK, Dame D, Pathak H, Padra AT, Yadav RL, Bijay-Singh (2003) How extensive are yield declines in long term rice-wheat experiments in Asia. Field Crops Res. 81:159-180

Mukhopadhyay D, Majumdar K, Pati R, Mandal MK (2008) Response of rainfed rice to soil test based nutrient application in Terai alluvial soils. Better Crops with Plant Food 92:13-15

Pasricha NS, Bansal SK (2001) Potassium fertility of Indian bench-mark soils. In: Papers and Presentations Section www.ipipotash.org.

Ramamurthy B, Bajaj JC (1969) Soil fertility map of India, Indian Agricultural Research Institute, New Delhi.

Reddy D, Prasad RN (eds) Long-term fertility management through integrated plant nutrient supply. Indian Institute of Soil Science, Bhopal, India, pp. 1-335.

Rich CJ (1972) Potassium in soil minerals, Proceedings of 9th Colloquium of International Potash Institute, Switzerland, pp 15-31

Sanyal SK, Majumdar K, Chatterjee S (2009) Influence of mineralogy on potassium availability in Indian soils and its implication on current nutrient use ratio. Paper presented in the brainstorming session on crop response and nutrient ratio, National Academy of Agricultural Sciences, New Delhi, pp 13-36

Sanyal SK, Majumdar K (2001) Kinetics of potassium release and fixation in soils. In: Potassium in Indian agriculture, Potash Research Institute of India, Gurgaon, India & International Potash Institute, Switzerland, pp. 9-31.

Sanyal SK, Chatterjee S (2007) Efficient use of soil, water and plant nutrients for food and environmental security. Indian J Fertilizers 3:71-88

Sarma VAK (1976) Mineralogy of soil potassium. Bulletin Indian Soc Soil Sci. 10: 66-77

Sekhon GS (1999) Potassium in Indian soils and crops. Proc Indian National Science Academy. B65: 83-108.

Sen P, Majumdar K (2006) Spatial variability in soil physico-chemical properties and nutrient status in an intensively cultivated village of West Bengal. Proc Fifth Intern. Conf Asian Federation for Information Tech Agriculture, Bangalore, India. Macmillan Advanced Research Series, pp 653-660

Sen P, Majumdar K, Sulewski G (2008) Importance of spatial nutrient variability mapping to facilitate SSNM in small land holding systems. Indian J. Fertilizers 4: 43-50

Sharma, SK (2003) Characterization and mapping of rice-wheat system: Its changes and constraints to system sustainability. NATP (PSR 4.1) Final Report, (2003-04), New Delhi

Singh M, Singh VP, Reddy DD (2002) Potassium balance and release kinetics under continuous rice-wheat cropping system in Vertisol. Field Crops Res 77: 81-91

Sparks DL, Huang PM (1985) Physical chemistry of soil potassium. In: RD Munson (ed.) Potassium in agriculture. Soil Sci Soc America, Madison, Wisconsin, pp 210-276

Subba-Rao A, Rupa TR, Yadav RL (2001) Assessing potassium needs of different crops and cropping systems in India. In: Papers and Presentations Section of www.ipipotash.org, pp 184-215

Subba-Rao A, Rao S (1996) Potassium status and crop response to K in different Agro-Ecological Regions in India. IPI Research Topics No. 20, International Potash Institute, Basel, Switzerland, pp 1-57

Swarup A, Rao S (1999) Current status of crop response to nutrients: Experiences from AICRP on LTFE. Fertilizer News 44 (4): 27-40

Tandon HLS (2004) Fertilizers in Indian agriculture – from 20th to 21st Century, FDCO, New Delhi. Pp 240

Tiwari KN (1985) Changes in potassium status of alluvial soils under intensive cropping. Fertilizer News 30:17-24

Tiwari KN, Sharma SK, Singh VK, Dwivedi BS, Shukla AK (2006) Site specific nutrient management for increasing crop productivity in India. Results with rice-wheat and rice-rice systems PDCSR, Modipuram and PPIC India Programme Gurgaon, pp 92

Yadav RL, Prasad K, Gangwar KS (1998) Prospects of Indian agriculture with special reference to nutrient management under irrigated systems. In: Swarup A, Damodar Reddy D, Prasad RN (ed) Long term fertilizer management through integrated plant nutrient supply. Indian Institute of Soil Science, Bhopal, India, pp 1-325

Yadav RL, Dwivedi BS, Kamta-Prasad, Tomar OK, Shurpali NJ, Pandey PS (2000) Yield trends and changes in soil organic-C and available NPK in a long-term rice-wheat system under integrated use of manures and fertilizers. Field Crops Res 68: 219-246

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GIS based soil fertility mapping for SSNM at village level in China: A case study in Shanxi province

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Abstract Rapid development of information technology provides an opportunity to improve soil nutrient management by using the advanced technology. In this study, Ershilipu village of Xinzhou city in Shanxi Province, which encompassed 245 ha and consisted of 443 farmer's plots, was selected as experimental sites to develop the approach to meet the needs of site-specific nutrient management for the small scale operation under family responsibility system in China. Two hundred and eighty plow layer (0-20 cm) soil samples were collected on a 100 ×100 m grid prior to the plots being sown for maize. Soil pH, organic matter (OM), available P, K, Zn, and other nutrients were measured. The results showed that OM, P, Zn and Fe were the main limiting factors in the soil. Spatial variability of tested soil properties in the experimental village was observed. Great variation was observed in soil OM, P, S, Zn and B, and small spatial variation in soil K resulting from the little fertilizer input. The spatial variability of soil OM and Ca relied mainly on regional factors. The variability of soil nutrient was greatly related to fertilization history, fertilizer application level, and soil texture. Site-specific nutrient management (SSNM) based on regionalized balanced fertilization helped to produce higher yield and income due to rational nutrient supply to crop.

Keywords SSNM • GIS • Soil nutrients • Spatial variability

Abbreviations DGPS: differential global positioning system; OM: organic matter; SSNM: site specific nutrient management

Introduction

Soil nutrient management with information technology is an important part of information agriculture (Atherton et al. 1999; Borgre and Mallarino 1997; Bouma

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et al. 1999). Compared with developed countries, China is far behind in terms of information technology use in soil nutrient management (Jin and Jiang 2000). The small scale farmer's farmland and variability in their fertilization practices caused the great variability in soil nutrient status. A fertilizer application survey investigation in Shanxi province indicated that the percentage of time that N application rate exceeded 250 kg N ha^{-1} was 20 percent for wheat and 25 percent for maize, and the percentage of time that N application rate less than 150 kg N ha^{-1} accounted for 56 percent for wheat and 53 percent for maize (Yang et al. 2008). Continuous cropping without balanced and efficient use of fertilizers has contributed to not only losses in yield and profit, but also to environmental problems such as groundwater nitrate-N contamination and eutrophication of rivers. Therefore, how to manage soil nutrient for the small scale operation with information technology is of great challenge in managing soil nutrient.

In China, due to the small-scale farm size and the cost of soil testing, it is impossible to give fertilizer recommend fertilizer based on each farmer. Usually, the same amount of fertilizer is recommended for a 15- to 20 ha field irrespective of the soil nutrient variability within the field. Thus, some areas of a field will receive too much fertilizer, whereas other areas will receive too little. A better understanding of the spatial variability of soil nutrients is required as a basis of soil nutrient management and rational fertilizer application (Hammond 1994; Franzen et al. 1996). Site-specific nutrient management in developed countries is based on a large scale of farm size with a high level of mechanization. With the rapid progresses of rural development and thereafter movement of farmers working in the city, and the policy on stimulation of the farm land transition to the larger size, fertilizer precision management based on soil nutrient variability would inevitably make great progress.

In this study, a systematic analysis of soil nutrient variability in a maize production area associated with the application of corresponding management approach was carried out. The objectives were 1) to investigate spatial variation of soil nutrient status and its distribution; 2) to develop nutrient management strategy based on nutrient variation; and 3) to evaluate the effect of nutrient management on yield and profits.

Materials and methods

Location of trials

The trials were located at Ershilipu village, Boming town, Xinzhou city, Shanxi provine. The tested soil was Fluvo-aquic. The site consisted of 443 farmers (244 ha), with an east longitude of 112°17' to 112°58' and a north latitude of 38°13' to 38°41'. The local climate is semiarid monsoon, with an average annual rainfall of 405 mm, average temperature of 8.5^0 C, and a frost free period about 160 days.

Soil sampling and analysis

A total of 280 soil samples from 0-20 cm depth were collected on a 100×100 m grid in the study areas of guided by using differential global positioning system (DGPS) technology with a trimble 132 GPS receiver. All soil samples were air-dried and ground through 2 mm sieve prior to analysis. The soil nutrients were determined with procedures applied by the Chinese Academy of Agricultural Sciences (CAAS) and International Plant Nutrition Institute (IPNI) Cooperative Soil and Plant Analysis Laboratory and the National Laboratory of Soil Testing and Fertilizer Recommendation of CAAS as described by Portch and Hunter (2002). Available P, K, Cu, Fe, Mn and Zn of the soil samples were extracted using 0.25 M/L $NaHCO_3$, 0.01 M/L EDTA and 0.01 M/L NH_4F. The concentration of P in the extraction was measured by the molybdenum blue colorimetric method. Concentration of K, Cu, Fe, Mn and Zn were determined using an atomic absorption spectrophotometer. The organic matter (OM) of the soil samples was extracted with an extracting solution containing 0.2 M/L NaOH, 0.01 M/L EDTA and 2 percent methyl alcohol, and the concentration of OM in the extract was determined by colormetry method. Soil pH was measured in a 2.5:1 soil-water suspension using a glass pH electrode. Soil nitrate-N was extracted with a 2 M/L KCl solution, and the concentration of nitrate-N in the extract was analyzed using an ultraviolet spectrophotometer at 220 and 275 nm (Chen et al. 1995; Wang et al. 2004).

Data analysis

Descriptive statistics and geo-statistics were used to analyze the data. ANOVA was calculated using SPSS 12.0 for Windows. The structure of spatial variation was analyzed through semivariograms using GS+ for Windows 3.1. Spatial distribution was analyzed through kriging interpolation using ArcGIS 8.0 software.

A semivariogram from the set of sample data is calculated using the following equation (Chilès and Delfiner 1999):

$$\gamma(h)=[1/2N(h)]\,\Sigma\,[Z(x_i+h)-Z(x_i)]^2 \qquad (1)$$

Where $\gamma(h)$ is the semi-variance for separate distance class h, $N(h)$ is the number of sample pairs at each distance interval h, $Z(x_i)$ is the value of the variable Z at sampled location x_i and $Z(x_i+h)$ is the value of the variable Z at a distance h away from x_i.

Parameters defining semivariogram models are nugget (variability at a smaller scale than the sampling internal and/or sampling and analytical error), sill and range. The range of the semivariogram is defined as the distance at which the variogram stabilizes around a limiting value, the sill, which can be approximately by the total variance of $Z(x_i)$. The sill expresses the distance (range) beyond which samples are not correlated.

Kriging of geo-statistics is an optimum interpolation technique for marking unbiased estimates of regionalized variables at unsampled locations in which the structural properties of the semivariogram and the values of a soil variable *Z* at an unsampled point X_0 is estimated by the formula (Chil s and Delfiner 1999):

$$Z(X_0) = \sum_{i=1}^{n} \lambda_i Z(X_i) \qquad （2）$$

Where X denotes the set of spatial coordinates (X_1, X_2), *n* is the number of neighboring samples and λ_i are the weights associated with the sampling points Xi. The predicted value $Z(X_0)$ is a weighted average of the values *Z* at *n* surrounding points.

Results

Status of soil nutrients

Available nutrient contents of surface soil samples from the experimental village were determined using the systematic approaches for soil nutrient evaluation (Portch and Hunter, 2002). Table 1 showed that most of the soils were low in soil OM, and deficient P, Zn and Fe, with the percentage of soil samples below the critical value being 100, 86, 94 and 77, respectively. About 23percent of the soils were relatively low in K, whereas soil S, Mn and Cu contents were above medium evaluation levels, with average values of 44.6 mg l^{-1}, 6.1 mg $l^{-1}$and 1.4 mg l^{-1}, respectively. Soil Ca, Mg and B contents were much higher than the critical values. Great variation existed in soil OM, P, S, Zn and B content with C.V. of 47.5percent, 46.0percent, 38.5percent, 37.6percent and 42.0percent, respectively (Table 1).

Spatial variation of soil nutrients

Semi-variograms analysis revealed a distinct different degree of spatial variability of soil nutrients. Cambardella et al. (1994) reported that spatial variability for a regionalized variable may be divided into three classes: strong, moderate and weak spatial dependence, corresponding to a nugget to still ratio $[c_0/(c_0+c)]$ of <25percent, 25-75percent and 75percent, respectively. About 20percent and 23percent of the spatial variability for OM and Ca were due to random factors associated with human activities (such as fertilization, crop varieties, management levels, etc), which demonstrated that spatial variability for soil OM and Ca was mainly relied on regional factors (e.g. topography, climate and soil matrix). The other nutrient regional factors, such as climate, soil type, fertilization or human activities. The proportion of spatial variability for soil pH, P, K, Mg, S, B, Cu, Fe, Mn and Zn were 58 percent, 70 percent, 26 percent, 56 percent, 68 percent, 29 percent, 59 percent, 50 percent, 41 percent and 74 percent, respectively, indicating that their spatial correlations were moderate (Table 2).

Table 1 Soil OM, available nutrient and pH in the maize production area under study

Item	Minimum value	Maximum Value	Mean	Standard deviation	C.V. (%)	The critical values of soil nutrient fertility evaluation	Percentage of soil samples below the critical values (%)
pH	7.7	8.2	8	0.1	1.2		
OM (%)	0.03	0.83	0.22	0.1	47.5	1.5	100
P (mg l^{-1})	1	43	8	4	46	12	86
K (mg l^{-1})	47	137	88.3	16.6	18.8	78	23
Ca (mg l^{-1})	1363	4068	2594	507	19.5	401	0
Mg (mg l^{-1})	142	490	274	55.3	20.2	122	0
S (mg l^{-1})	8	97	44	17	38	12	3
Zn (mg l^{-1})	0.6	4.6	1.2	0.5	37.6	2	94
Mn (mg l^{-1})	3.5	14.9	6.1	1.4	23.0	5	18
Fe (mg l^{-1})	4.5	17.0	8.4	2.3	27.0	10	77
Cu (mg l^{-1})	0.9	4.0	1.4	0.3	24.9	1	4
B (mg l^{-1})	0.3	5.0	2.2	0.9	42.0	0.2	0

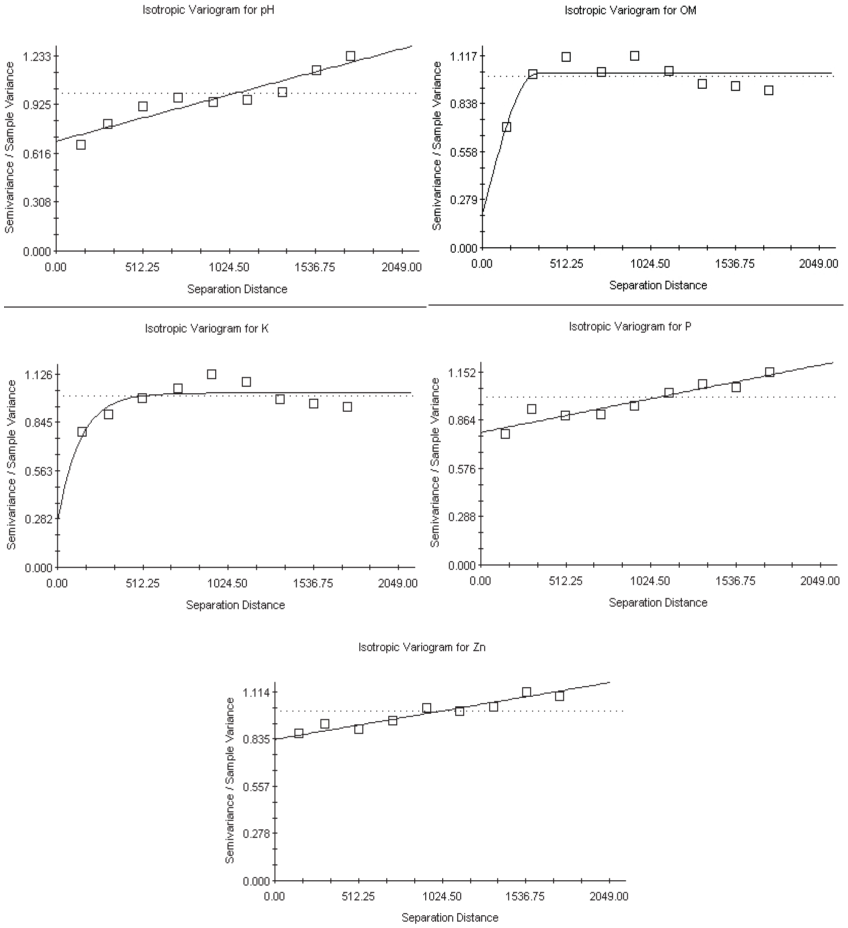
Table 2 Semivariograms analysis for soil pH, OM and nutrients in the study area

Item	C0 Nugget-to sill	C+C0 Sill	C0/ (C+Co)	Range (m)	Model	R^2
pH	0.69	1.19	0.58	1739	L	0.882
OM	0.20	1.01	0.20	328	S	0.686
K	0.27	1.02	0.26	405	E	0.614
Ca	0.31	1.35	0.23	1949	S	0.999
Mg	0.69	1.23	0.56	1739	L	0.877
P	0.79	1.13	0.70	1739	L	0.891
S	0.78	1.14	0.68	1739	L	0.799
B	0.30	1.03	0.29	336	E	0.629
Cu	0.70	1.18	0.59	1739	L	0.755
Fe	0.58	1.17	0.50	1995	E	0.909
Mn	0.42	1.02	0.41	418	S	0.965
Zn	0.83	1.12	0.74	1739	L	0.905

Spatial distribution of soil nutrients

Soil nutrient contour map was made using Kriging interpolation and using evaluation classes of the systematic approaches for soil nutrient status evaluation (Fig. 2). The contour map of soil properties may directly reflect the spatial distribution characteristic of diversified soil nutrient element; also help to understand the nutrient status to provide the foundation to rational fertilization. The integrated map was conducted with overlaying the nutrient contour map and farmer's plot map to understand soil nutrient status of each farmer's plot. If soil nutrient contents in most areas of a farmer's plot were within one evaluation class, soil nutrient contents for all area of that farmer's plot were considered to fall within one evaluation class. This made it possible to improve the fertilizer recommendation system from one recommendation from 15-20 ha field to a site-specific nutrient management for a specific farmer's plot.

Fig. 2 Semivariograms for soil pH, OM, P, K and Zn in the study area



The distribution area with high P and K contents which was over the critical level was located in the middle of the eastern part of the village, and that with medium P and K nutrient level was distributed in the western part of the village. The distribution area with lowest P and K contents was located at the south and north bottom of the village. Soil Zn distribution map was similar to soil P (Fig. 3). It was indicated that great spatial variation existed in soil nutrients, and spatial distribution similarity was observed in the soil P, K and Zn.

Yield and profit evaluation of SSNM

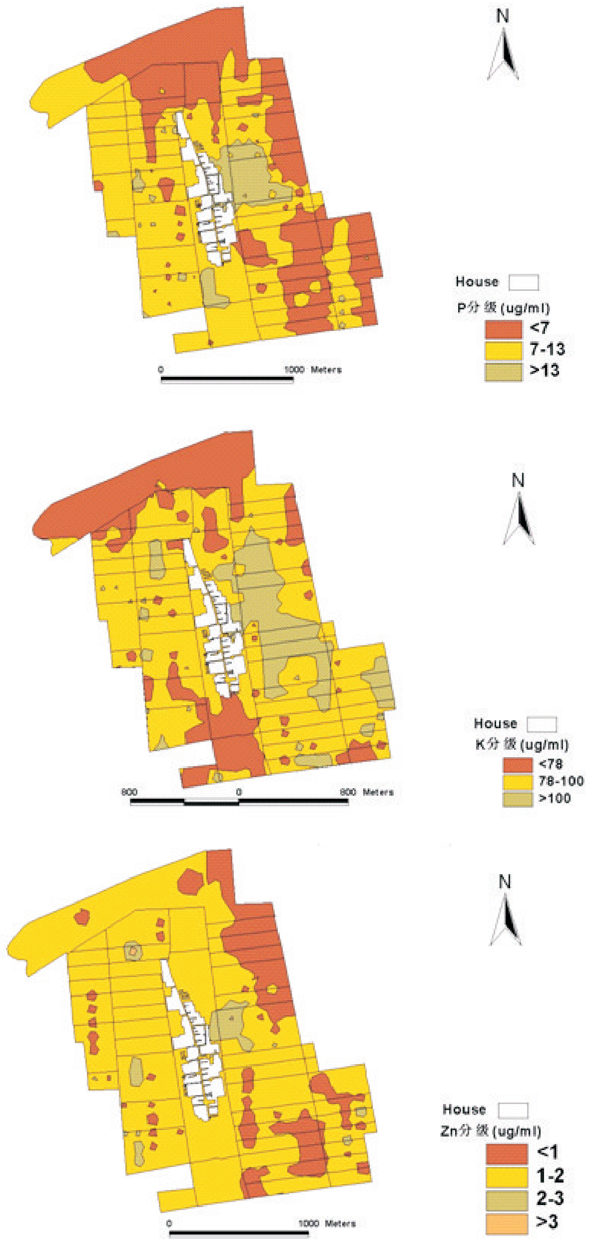
The site specific fertilizer recommendation (SSNM) significantly increased corn yield and farmer's income compared to farmer's conventional practice. The average yield of spring maize increased by 12.4percent and average farmer's income increased by 798 Yuan/ha (117US$/ha) from SSNM fertilizer recommendation compared to farmer's conventional practice in the experimental site. These results showed that site-specific soil nutrient management based on farmer's field unit can help to produce higher yield and income due to rational nutrient supply to crop.

Discussion

Previous and the current study indicated that great variation existed in soil nutrient due to the small scale farm size production, different cropping system and different fertilization custom (Yang et al; 2000; Huang et al., 2003, 2006). The result obtained in the current study indicated that great variation for soil OM, P, and Zn existed in the study area, and the survey of crop production history and fertilizer application indicated that a close relationship existed between the spatial variability of the soil nutrients and the crop production history and fertilizer application rates. For example, the higher contents of soil P, K and Zn at mid eastern of the village were resulted from the corresponding vegetable production with heavy inorganic and organic nutrient input. The medium nutrient levels for P and K were located at the western part, where was the maize production area with certain nutrient input less than those from vegetable production area. The reasons for lower contents of P and K located at south and north bottom parts were the soils with sandy loam texture and relatively low nutrient inputs from farmers.

The site-specific nutrient management practices have been carried out based on the variation of soil nutrients. For the areas with great nutrient spatial variation, the fertilizer recommendation would regionalize the study area with variable

Fig. 3 Distribution of soil P, K and Zn in the experimental site



fertilizer application rate; while for the areas with small nutrient spatial variation, an uniformed fertilization rate would be recommended. Yang et al. (2000) reported that the application of grid sampling and variable rate application technology in a 54-ha cotton field increased fertilizer efficiency, with a net profit of 5313 RMB Yuan ha^{-1} (RMB Yuan 8.26 = US$ 1) higher than that obtained with local fertilization practice. Huang et al. (2003) reported that the incorporation of regionalized balanced fertilization technology into wheat and corn farming practices significantly increased income by 590-1350 RMB Yuan ha^{-1}. The results obtained in this study demonstrated that maize yield increased by 12.4percent and profit increased by RMB Yuan 798 ha^{-1} with the regionalized balanced fertilization compared with that by farmer's practice. It was indicated that site specific nutrient management practice based on nutrient spatial variation with regionalized balanced fertilization is a promising nutrient management practice in China.

Conclusion

The great variability in farmer's fertilization practices resulted in the great spatial variation in soil nutrient status in the study area. The soil OM, P, Zn and Fe was deficient in high percentage of nutrient values below the critical values. Large variation in nutrient contents was observed in soil OM, P, S, Zn and B. On the contrary, soil K had a smaller spatial variability due to little nutrient input as fertilizer. The variability of soil OM and Ca attributed mainly to random factors and regional factors (e.g. topography, climate and soil matrix), and that for pH and other nutrients related to more closely to random factors related to human activities such as fertilization, cropping system, etc. The contour map of soil properties may directly reflect the spatial distribution characteristic of diversified soil nutrient, and help to understand the nutrient status to provide the foundation to rational fertilization; Site-specific nutrient management integrated with regionalized balanced fertilization based on farmer's field plot can help to produce higher yield and income due to rational nutrient supply to crop.

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References

Atherton BC, Morgan MT, Shearere SA, Stombawgh TS, Ward AD (1999) Site-specific farming: A perspective on information needs, benefits, and limitations. J Soil Water Conserv 54:455–461

Borges R, Mallarino AP (1997) Field-scale variability of phosphorus and potassium uptake by no-till corn and soybean. Soil Sci Soc Am J 61: 846-853

Bouma J, Stoorvogel J, van Alphen BJ, Booltink HWG (1999) Precision Agriculture, and the changing paradigm of agricultural research. Soil Sci Soc Am J 63:1763-1768

Cambardella CA, Moorman TB, Noval JM, Parkin TB, Karlen DL, Turco RF, Konopka AE (1994) Field scale variability of soil properties in central Iowa soils. Soil Sci Soc Am J 58: 1501-1511

Chen MC, Zhang Q, Yang JL (1995) Selection and verification of methods for determination of nitrate in soil extracts (in Chinese). J Shanxi Agric Sci 23:31-36

Chil s JP and Delfiner P (1999) Geostatistics: Modeling spatial uncertainty. John Wiley, New York

Franzen DW, Hofman VL, Halvorson AD, Cihacek LJ (1996) Sampling for site-specific farming: Topography and nutrient considerations. Better Crop 80:14-18

Hammond MW (1994) Comparison of phosphorous and potassium utilization with conventitional and variable fertility management. Better Crop 78: 22-23

Huang SW, Jin JY, Yang LP, Bai YL (2006) Spatial variability of soil nutrients and influencing factors in a vegetable production area of Hebei Province in China. Nutr Cycl Agroecosyst 75:201-212

Huang SW, Jin JY, Yang LP, Cheng MF (2003) Spatial variability and regionalized management of soil nutrients in thegrain crop region in Yutian county (in Chinese). Acta Pedologia Sinica 40:79-88

Jin J, Jiang C (2000) Spatial variability of soil nutrients and site-specific nutrient management. Proceeding of International Conference on Engineering and Technological Sciences, New World, Beijing, pp 137-141

Portch S, Hunter A (2002) A systematic approach to soil fertility evaluation and improvement. Special publication No.5 PPIC China Program, Hong Kong. p 62

Wang SG, Hou YL, Guo W (2004) Study on the effect of different fertilizer-soil ratios on NO_3 N concentration (in Chinese). Plant Nutr Fertilizer Sci 10:148-151

Yang B, Chen MC, Yang ZP, Zhang JJ , Zhang Q (2008) Nutrient resources management and nutrient balance of wheat and maize in Shanxi (in Chinese with English abstract). J Shanxi Agri Sci 36:3-7

Yang LP, Jiang C, Jin JY, Zhang FM (2000) Study on site-specific nutrient management in cotton field (in Chinese). Sci Agric Sinica 33: 67-72

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Potassium management for crops in soils of Orissa

D Jena • AK Pal • KK Rout

Abstract The soils of Orissa are broadly classified as Alfisols, Inceptisols, Entisols and Vertisols. Total potassium content in soils varies between 0.3 to 3.0%. Non-exchangeable K constitute 21 to 61% of total K, whereas exchangeable K 12.5 to 35.7%. Production and productivity of major crops in the state are lower than national average probably due to imbalance and lower fertilizer consumption rate (62 kg ha^{-1}). Potassium application in the state was neglected up to 80's due to lack of response and thereafter crop responses are increasing in time and space. Low application of K leads to depletion of K to the extent of 242.8 thousand tones per annum. In long-term fertilizer studies with rice-rice and rice-pulse cropping systems, the sustainability of crop yield was threatened in absence of K application. In many production systems in the state, the non-exchangeable K meets the K requirement and sustains the level of production. Higher correlation between HNO_3-K and K balance and yield suggests the inclusion of this method in soil testing programmes in the state. Optimal and super-optimal doses of K could not sustain the yield and K depletion. Hence, a need to reschedule the K dose for crops. An holistic management of K could be possible by applying adequate amount of K on the basis of soil test, recycling of crop residues and addition of rural and non-toxic urban compost in different cropping systems under varying agro-ecological regions. A sustainable fertilizer management strategy should ensure farm productivity, optimum economic return and soil health.

Keywords Acid soil • integrated potassium management • potassium balance • potassium mining • step-K

Introduction

The state of Orissa located in the Coromondal coast of India has a tropical monsoon climate characterized by high humidity, high rainfall (1497 mm) and short and medium winter. It is the 10th largest and 11th populous state accounting about 5% of the geographical area and 4% of the population of the country. The

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geographical area of the state is 15.57 m ha, out of which 6.2 m ha are arable land. Agriculture contributes 28% to net state domestic production and employ 64% of the work force.

Rice is the principal food grain of the state and occupies 50% of the total cultivated area followed by pulses (22%), oilseeds (9%), vegetable (7%) and other crops like fruits, spices, sugarcane, jute, etc. (12%). The production and productivity of major crops in the state are below the Indian average. In addition to soil acidity, low fertilizer consumption (57 kg ha^{-1}) and imbalanced use of fertilizer are the reasons for low productivity. Although the state has experienced upward trend in fertilizer use from 7.6 kg ha^{-1} (1980) to 62 kg ha^{-1} (2008 – 09), the ratio of N to K fertilizer is still wide, although narrowed down from 5.9 during 1980 to 4.43 during 2008– 09.

During 1960 to 1990, India experienced a dramatic change in food grain production with introduction of high yielding varieties and improved management strategies. Later on, the yield level remains stagnant or declined even with increase in level of input. Evidence of declining partial or total factor productivity is already available. Depletion of soil K was one of the reason of yield decline in long term fertilizer experiment (Ladha et al. 2003).

The experience with rice – rice cropping system which started during 1972 – 73 in lateritic (Aric haplaquepts) soil of Bhubaneswar showed lack of response to K till 1983 and thereafter the response increased from 2.90 q ha^{-1} to 8.95 q ha^{-1}. In most of the cropping systems practiced in India, K balance is negative, however the negative balance is not reflected in available K (Water soluble + Exchangeable K) status over years of cropping. A huge negative balance of 242.8 thousand tones per year in Orissa (Mishra and Mitra 2001) and proposed deficit of 8.1 million tones per year by 2020 (Katyal 2001) in Indian agriculture is a matter of concern. We have attempted to discuss K dynamics and management practices for major cropping systems of Orissa under diverse agro-ecological situations.

Soils of Orissa

The state of Orissa is situated between $17^{0} 47^{/}$ and $22^{0}33^{/}$ N latitude and between $81^{0}21^{/}$' and $87^{0}30^{/}$ E longitude. Based on physiography and relief, the state is broadly classified into 4 broad physical divisions, namely Northern plateau, Central tableland, Eastern Ghats and Coastal plains. The soils of Orissa come under 4 orders namely Inceptisols (7.49 m ha), Alfisols (5.62 m ha), Entisols (1.53 m ha) and Vertisols (0.93 m ha). Inceptisols occupy 48% of total geographical area (TGA), represent older alluvial and mixed red and yellow soils. These soils have weak profile development and are at the beginning stage of soil formation. Alfisols (36% of TGA) represent red, laterite and lateritic and brown forest soils. These soils are base rich mineral soil and characterized by light coloured surface horizon over a clay enriched argillic subsurface horizon. They are rich in Fe, Al oxides and more strongly weathered that Inceptisols. Entisols (10% TGA) represent alluvial, coastal saline and colluvial soil. These soils are recently formed soil with little development of pedogenic horizons and are seen in flood plains in delta areas. Vertisols (6% TGA) are black or regur and occurs in specific locations of the state. These soils are black or dark coloured, uniform with gilgai micro relief. The clay content is more than 30% and clay minerals are mostly smectitic. These soils swell on wetting and shrink on drying with cracks of more than 1 cm wide and have angular blocky structure. About 70-75% of soils of Orissa are acidic and support important production systems including cereals, pulses, oilseeds, horticultural crops, plantation crops and forestry. The production and productivity of crops in Orissa are low (Table 1) as compared to all India average due to both deficiency and toxicity of plant nutrients, low consumption of fertilizer and imbalanced use of fertilizer (Table 2).

Table 1 Productivity of different crops in Orissa as compared to all India (2004-05)

Crops	Productivity (q ha^{-1})	
	Orissa	All India
Rice	14.5	19.8
Wheat	13.3	26.0
Maize	13.2	19.0
Arhar	6.8	6.6
Groundnut	15.1	10.2
Sugarcane	686.0	647.5
Potato	94.9	179.2

Source: Agricultural Statistics of Orissa 2008

Table 2 Fertilizer consumption rate and ratio of N and K in Orissa

Year	N+P_2O_5+ K_2O (kg ha^{-1})	N: K_2O ratio
1980	7.6	5.9
1990	21.0	5.1
2000	31.0	6.7
2005-06	46.0	5.8
2006-07	52.0	4.9
2007-08	57.0	4.4

Source: Agricultural Statistics of Orissa 2008

Mineralogy of soils

Important K bearing minerals in soils of Orissa are muscovite, biotite and feldspar. Release of K to crops depends on the nature of dominating K bearing mineral. On the basis of K release power, the minerals are arranged in the order of: biotite > muscovite > orthoclase > microcline. The inherent status of K in soils of Orissa is mainly governed by the soil mineralogy. The microcline is the most common K-feldspar in the soils of Orissa (Sahu et al. 1995). In Alfisols, orthoclase constituted 9.8 to 41.1% while muscovite mica from nil to 6.1% (Table 3). The presence of high content of light minerals (orthoclase feldspar) in fine sand fractions may be attributed to moderate weathering in the environment. High temperature with alternate wet and dry season in humid sub-tropical climate of Orissa are also conducive for development of illite in the clay fractions due to alternation and partial hydrolysis of feldspar and mica (Sahu et al. 1983). The occurrence of Kaolinite in these soils is also expected due to leaching of bases. In the Inceptisols, orthoclase content varies 7 to 42.4 %. Except Shyamakhunta and Motto (saline soil), mica content varies between 1.0 to 4.8 %. These soils in general are, neutral to slightly alkaline and have high base saturation capacity with Ca^{2+} and Mg^{2+} dominating in the exchange complex. These conditions are favorable for the formation of smectites in the clay fractions (Sahu et al. 1983). Alternation of K-feldspar might have led to the formation of illite in clays. The Entisols are found in Delta area of Orissa due to deposition of silt and clay by the action of flood and contained higher amount of orthoclase (27.1 to 38.6%) and mica (1.7 to 17.4 %). High mica content in the sand fraction indicates lack of weathering and the soils are rich in K. High base saturation with mild acidic to neutral soil reaction must have favoured formation of smectites besides illites (Sahu et al. 1990)

Table 3 Mineral composition of different soil orders of Orissa

Location	Classification	Orthoclase (%)	Mica Muscovite (%)	Clay mineralogy in order of abundance
		Alfisols		
Phulbani	Oxic Paleustalfs	24.6	6.1	I,K
Bhubaneswar	Rhodic Paleustalfs	41.1	-	I,K
Khurda	Ferric Plinthustalfs	37.6	-	I,K
Semiliguda	Oxic Paleustalfs	9.8	1.9	K,I
Suakati	Ultic Paleustalfs	31.0	-	K,I
Muktapur	Lithic Plinthustalfs	15.4	-	I,K
		Inceptisols		
Bhubaneswar	Eutrochrepts	16.0	1.0	I,M,K
Shymakhunta	Aeric Ustochrepts	30.5	-	K,I,M
Ranital	Typic Haplaquepts	7.0	2.5	M,I,K
Motto	Vertic Haplaquepts	41.5	-	K,I,M
Keshpur	Typic Haplaquepts	42.5	4.8	M,C,I,K
		Entisols		
Jasuapur	Typic Ustifluvents	27.1	14.8	I,M,K
Kendrapara	Typic Usterthents	33.0	1.1	I,M,K
Chilika	Prammaquents	22.5	3.1	K,I,M
Astaranga	Typic Haplaquents	38.6	4.3	M,I,K
		Vertisols		
Bhawanipatwana (Arkabali)	Typic Pellusterts	12.4	2.7	M,I
Luisinga	Ustalfic Pellusterts	26.9	11.0	I,M

I = Illite, K= Kaolinite, M= Montmorillonite,C=Chlorite
Source : Sahu et al. 1995

The orthoclase and mica in Vertisols of Orissa varies between 12.4 and 26.9 % and between 2.7 and 11.0 %, respectively. Their transformation/alteration accounts for the occurrence of illite. Abundance of Ca^{2+} and Mg^{2+} in an alkaline environment favours the formation of montmorilonite in the clay fraction. Nayak et al. (2001) analysed the fine sand fraction (0.1 to 0.25 mm) of Alfisols and Inceptisols of university farm (OUAT) at Bhubaneswar and reported that quartz dominated (55.0 - 80.5 %) the fine sand fraction along with K bearing minerals like orthoclase feldspar (9.5 -31.0 %), biotite and muscovite mica (0.5 -2%). The Alfisols contained more K bearing minerals than the Inceptisols (Table 4). In fine sand fraction (0.1 -0.25 mm) of soils of Kanchinala micro watershed under coastal plains of Mahanadi delta of Orissa. Mishra (2008) observed a considerable amount of K bearing minerals like orthoclase, muscovite and biotite in upland, medium land and low land soils (Table 5). Higher amount of orthoclase was present in low land (20.6%) followed by medium land (19.2%) and upland

Table 4 Mineralogy of fine sand fraction in the soils of Central Research Station, OUAT, Bhubaneswar

Mineral Species (%)	Orders	
	Inceptisols	Alfisols
Quartz	80.5	55.0
Orthoclase Feldspar	9.5	31.0
Andelusite	0.5	1.0
Garnet	0.5	1.0
Muscovite	-	1.0
Biotite	2.0	1.0
Zircon	-	0.5
Chlorite	2.0	2.0
Rutile	0.5	-
Opaque	3.5	4.5
Unidentified mineral	1.0	2.0

Source: Nayak et al. 2001

Table 5 Mineralogy of fine sand fraction of Kanchinala micro watershed under coastal plains of Mahanadi delta, Orissa

Mineral Species (%)	Upland	Medium Land	Low land
Quartz	64.2	61.4	59.3
Orthoclase	16.5	19.2	20.6
Plagioclase	4.8	5.2	5.0
Calcite	0.3	1.6	2.0
Muscovite	3.5	3.0	2.8
Biotite	2.8	2.2	2.3
Garnet	2.2	1.8	2.0
Hornblende	1.5	1.2	1.2
Opaque	3.0	3.5	4.0

Source: Mishra 2008

(16.5%). On the other hand the content of muscovite and biotite was in the order of upland > medium land > lowland.

Weathering process is generally influenced by cationic environment, especially the base saturation of clays. An alkaline environment favours the formation of montmorillonite while acidic environment favours the formation of kaolinite and Mg rich environment produces vermiculite. Release of organic acids through decay of plant roots by microbes accelerates the process of weathering. In laterite soils under rice-rice cropping system (Pattanayak 1992) the allophane content was increased from 0.04 (initial value) to 0.048 in control, and 066 in 150% NPK treatment. Lower content of allophane (0.012) was observed in fallow treatment. Intensive cultivation of rice-rice cropping system for 18 years with 100% NPK increased the illite content. The content of interstratified smectite was higher in 100% NPK + FYM and illite with interstratified smectite in 150 % NPK treatment (Table 6).

Table 6 Occurrence of clay minerals as affected by long term manure and fertilizer applications in rice-rice cropping system (expressed as d-spacing in Mg saturation and glycolated clay)

Treatments	14-17 A^0	10.1-14 A^0	10.1 A^0	7.1 A^0	4.26 A^0
Control	27.5	27.0	19.1	27.4	0.8
100% NPK	29.5	30.3	16.2	24.0	-
100% NPK+FYM	35.0	33.6	11.5	19.2	0.7
150% NPK	36.2	14.7	18.9	29.7	0.6
Initial	35.5	28.7	13.8	23.4	0.6

Source: Pattnayak 1992

Potassium status

Soils of Orissa are considered as medium to high in available potassium. Coastal saline soils are high in exchangeable-K (56.6 to 624 mg kg^{-1}) and water soluble-K (117 to 624 mg kg^{-1}). Alluvial soils have wide rage of K status. The extreme low values of exchangeable-K and percent K saturation in alluvial and red soils indicated the higher K removal from non-exchangeable sites under high cropping intensity. The total K_2O content ranges from 0.30 to 1.20 % in laterite soils, 1.62 to 6.03 % in mixed red and black soils, 0.68 to 2.41% in alluvial soils, and 1.77 to 3.01% in coastal saline soils. Non-exchangeable K constitutes 21 to 64% of total K, highest being in alluvial soils where as the exchangeable K constitutes between 12.5 to 35.7 % of total K. In rice-groundnut growing soils of Alhagarh in Cuttack district (Pal et al. 2001) total K ranged from 950 to 2400 mg kg^{-1}. Ammonium acetate extractable K constitutes 3 to 12% , non-exchangeable K 14 to 45% and lattice-K 48-80% of the total K. Total K content in surface soils of an watershed in Khajuripada block of Kandhamal district with rice-pulse cropping system varied between 1100 to 2600 mg kg^{-1} (Das et al. 1997). Total K content increased with decrease in elevation of the watershed. In all the three profiles (foot hill, mid upland and medium valley), water soluble K decreased whereas non-exchangeable, lattice K and total K increased with depth, probably due to increase in clay content. Lattice K constitutes 53 to 73 %, non-exchangeable and exchangeable K from 24.8 to 41.8 and 2.8 to 3.7 % of total K, respectively.

Interrelationship of forms of K

Exchangeable, non-exchangeable, lattice and total K of 21 alluvial soil samples collected from rice-groundnut cropping system (Pal et al. 2001) and rice-pulse cropping system (Sahu 1994) in Badamba block of Cuttack district were positively correlated with each other The dynamic equilibrium was existed among different pools and depletion of K from one pool is replenished from the other pools of soil K.

Potassium transformation

The rate at which K is released from non-exchangeable sources is an index of the ability of soil to supply K to crops. The rate and magnitude of release depend on the level of K in soil solution and amount and type of clay minerals present in soil (Martin and Spark 1985). The contribution of release of non-exchangeable K to K-availability has been reported by several workers (Sparks 2000, Parker et al. 1989 b). The rate of release of non-exchangeable K is influenced by the degree of exposure of edges of clay minerals to the soil solution. In some soils the release of non-exchangeable K may be slow and restrict crop yield, where as in some cases it may be rapid to meet the K requirement of crops. The release kinetics of eight soil series in Indo-Gangetic plain of India (Sekhon et al.1992) showed that Kaolinite dominated alluvial soils and smectitic acidic alluvial soils in lower Gangetic plain showed lower rate of K release from the non-exchangeable fraction than that of illitic alluvial soils.

In rice-rice cropping system in Inceptisols and soyabean-wheat-cowpea in Vertisols (Typic Haplusterts), the total K uptake by crops exceeded the amount of K applied. The plots which did not receive K fertilizer (control, N and NP treatment) in soybean-wheat-cowpea system contributed K to the extent of 3129 to 9932 kg ha^{-1} from non-exchangeable source as against 1183 to 1891 kg ha^{-1} in rice-rice system. The results of LTFE trials clearly showed that mining of K occurred with N, NP and even with NPK application (Rupa et al. 2003)

Results from two long term fertilizer experiments conducted at Bhubaneswar with rice-rice cropping system and at Keonjhar with rice-oilseed/pulse cropping system representing two different agro-climatic regions of Orissa showed that in rice-rice cropping system there was sharp increase in available K in the first 10 years of cropping followed by a rapid fall between 1980-1983 and almost plateauing afterwards in all treatments except NPK+FYM treatment (Fig. 1). The treatment that received 100% NP but no K always recorded lowest NH_4OAC K followed by 50% NPK treatment. On the other hand 150% NPK treatment recorded highest value of NH_4OAC K followed by 100 % NPK treatment. In mixed red and black soil of Keonjhar with rice-mustard cropping system, the NH_4OAC K in surface increased rapidly by nearly 100% than the initial (144 kg ha^{-1}) probably due to bringing the uncultivated barren land under cultivation and increase in organic matter content (0.23 to 0.55%). Subsequently there was a gradual drop of NH_4OAC K to the extent of 25 to 75 kg ha^{-1} (Fig. 2)

Fig. 1 Variation in NH_4OAC extractable (available) K status of soil (3 years average) under long term manuring at Bhubaneswar centre

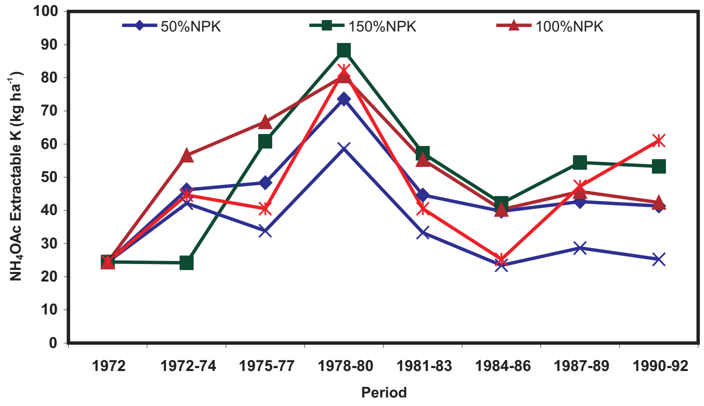
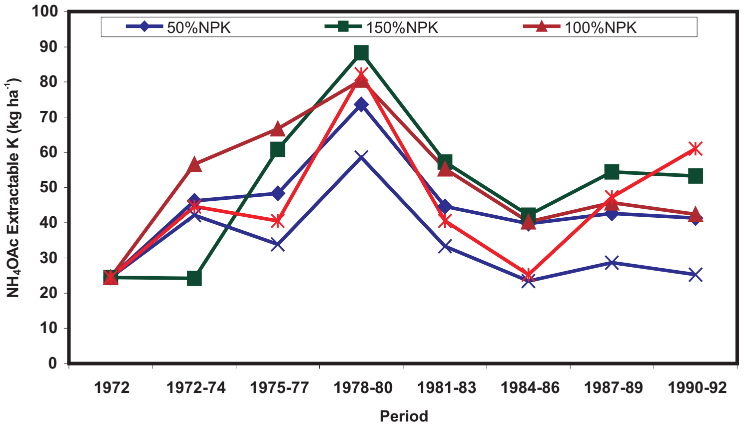
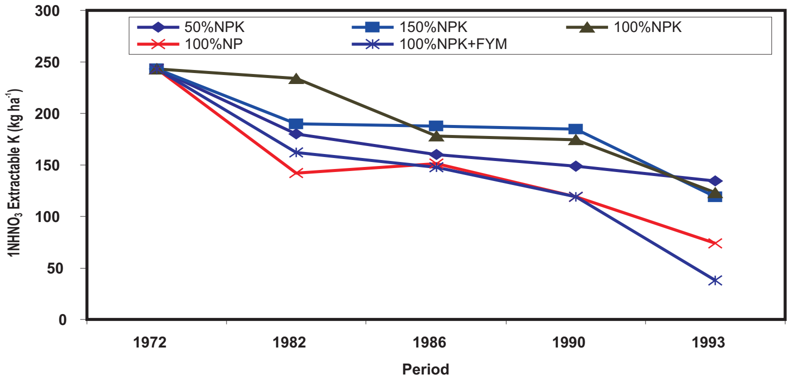


Fig. 2 Variation in NH_4OAC extractable (available) K status of soil under long term manuring at Keonjhar centre



There was a gradual decrease of HNO_3 –K over the years and after 20 years it reached almost 50% of the initial level particularly in the treatments that received K every year (Fig. 3). Maximum decrease was recorded in NP followed by NPK+FYM treatment. The decrease in latter treatment might be due to relatively much higher cumulative uptake of K by crops associated with higher biomass yield. The depletion of 1N HNO_3-K could maintain large amount of potassium in soil solution and exchange sites by reestablishing the equilibrium among different forms of K. Multiple correlation studies revealed that, both NH_4OAC and 1N HNO_3 extractable K in soil in various treatments of LTFE trials were significantly correlated to the K balance indicating a strong influence of K application and uptake on the extractable K status of surface soil.

Fig. 3 Variation in 1N HNO_3 extractable K over the years at Bhubaneswar



Dobermann and Fairhurst (2000) suggested K saturation as a better indicator for K supply of soils. He categorized rice soils with less than 1.5% K saturation as low K, with 1.5–2.5% K saturation as medium K and with more than 2.5% K saturation as high K soils. The K saturation of broad soil groups of Orissa were in the order of: black soils (5.54%) > coastal saline soils (4.32%) > laterite soils (2.7%) > alluvial soils (2.35%). Although K saturation of Orissa soils come under high category, still good response to K application was recorded in alluvial and laterite soils where as there was no response in coastal saline soils. However, optimum dose of K for crops in coastal saline soils is recommended to suppress Na uptake.

Contribution of subsurface K to plant uptake

Subsurface K contributes significantly to plant nutrition. The difference in mineralogy and K reserve in subsurface horizon influences the subsurface K availability. Results of 15 years of rice-rice cropping at Bhubaneswar revealed that although NH_4OAC –K of the surface layer was higher than the initial value, the sub surface layers showed a lower status as compared to initial value. On the other hand, there was substantial decrease in 1N HNO_3-K in all the layers indicating the contribution of non exchangeable K towards K nutrition of crops. Similar findings were also observed with respect to NH_4OAc–K and HNO_3 –K at Keonjhar after 10 years of cropping.

These results indicated that at Bhubaneswar NH_4OAc–K in different layers showed very poor correlation with K balance. On the contrary significant correlation existed between HNO_3–K of each layer and K balance (r=0.85**, 0.72** and 0.74** for 0-0.15, 0.15-0.30 and 0.30-0.45m layer), respectively. Around 68% of the variation of HNO_3 –K of 0-0.15 m layer were accounted for K balance. A measure of total K in all the three layers also shows a substantial variation from the initial value. A drop in total K at the end of 1987-88 was many times higher than the decrease in NH_4OAc–K and HNO_3–K indicating that weatherable K bearing minerals in surface and sub surface layers make a major contribution to plant uptake K. Singh et al. (2002 b) reported that application of organic manures along with urea –N increased the cumulative non – exchangeable K release and could maintain large amount of K in soil solution on exchange sites by reestablishing the equilibrium among different forms of K. In rice-rice cropping system at Bhubaneswar , NPK + FYM treatment encourage release of more non – exchangeable K under acidic environment to meet crop requirement of K. Wihandjaka et al. (1999) observed that mobilization of non-exchangeable K in flooded rice is due to root induced acidification and removal of K from soil solution by roots. Under flooded rice ecosystem, release of hydronium ion (H_3O^+) from roots and decomposition of organic manures and plant residue, actively counter act to replace structural potassium (Kirk et al. 1993). This was observed in rice- rice system at Bhubaneswar due to decrease in total K in all the three layers over 15 years of cropping.

Potassium release characteristics

Step K provides estimation of K availability from the non–exchangeable sources and constant rate K (CR-K) is a measure of difficulty available K of mineral lattice source. The K release characteristics of 21 surface soil samples of laterite soils with rice based cropping system revealed that step K was maximum in the 1st extraction and varied from 150 to 700 mg kg^{-1} and gradually decreased to zero in 6th and 7th extraction (Pal et al. 2001). Higher values of step K is associated with greater release of K from non–exchangeable K under stress condition. The CR- K, total step K and total exchangeable K in soils varies between 12-56, 140-1332 and 500-1592 mg kg^{-1}. The correlation coefficient of K release parameter with different forms of K showed that exchangeable, non–exchangeable, lattice and total K were positively correlated with each other suggesting the existence of dynamic equilibrium among the different pools of K in soil. Highly significant and positive correlation between step K with HNO_3 K indicates that HNO_3 K could serve as a good index of plant available non–exchangeable K in soil. In alluvial soils with rice based cropping system, the step K was maximum in the 1st extraction and varied between 104 and 1510 mg kg^{-1} and gradually decreased with increase in number of extraction (Sahu 1994). Constant rate K (CR K) values varied from 8 to 44 mg kg^{-1}, which indicate adequate supply of lattice K to plants. The total extractable K varied from 442 to 1792 mg kg^{-1} soil. In a long term fertilizer experiment (LTFE) with rice-rice cropping system sequential stepwise extraction with boiling HNO_3 yielded two categories of K viz. CR K, released from mineral lattice at a fairly constant rate and step K released from edge and wedge zone of micaceous minerals, the amount of which was negligible after 3rd extraction (Senapati 1993). There was little difference of CR K in different treatments (Table 7).

There was a quite large difference in step-K. The NPK treatments recorded much higher step K values compared to NP treatments in all the three layers of soil indicating their potentiality to release K for crop uptake. As compared to the initial level, Step K declined by 55% in NP treatment in 0-15 cm layer. When both surface and subsurface layers are taken into account, the decrease in Step K was 45% in NP treatment, 4% in 150% NPK and 19% in 100% NPK treatment. The decrease in 100% NPK +FYM was slightly more (27%) due to higher crop uptake.

Crop response to applied potassium

Balanced use of fertilization enhances crop yield, crop quality, farm profit and maintain soil health and crop productivity of the land. The grain yield of kharif rice

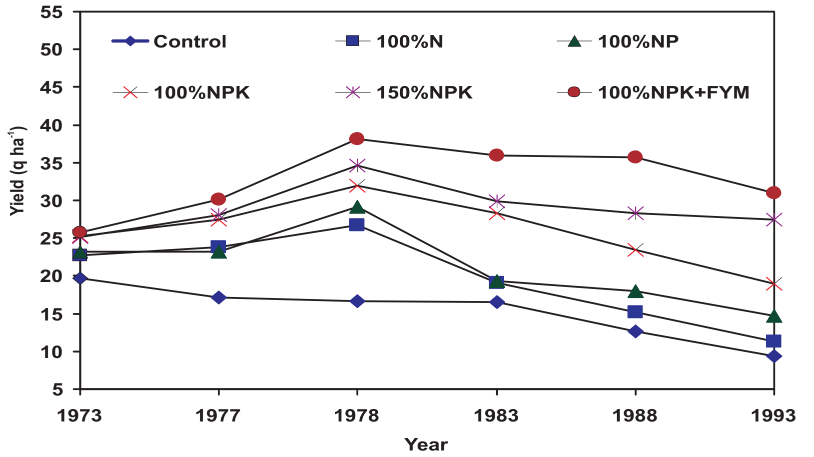
Table 7 Cumulative effect of treatments on Step -K and CR-K after 22 years of rice-rice cropping at Bhubaneswar

Treatments	Step-K (mg kg^{-1})			CR-K (mg kg^{-1})		
	0-0.15 m	0.15-0.30 m	0.30-0.45 m	0-0.15 m	0.15-0.30 m	0.30-0.45 m
NP	43	51	74	15	16	22
NPK	84	54	108	16	18	24
NPK(150%)	98	88	105	17	18	25
NPK+FYM	72	54	97	16	17	24
Initial	96	97	111	17	20	26

Source: Senapati 1993

in rice-rice cropping system of LTFE trial in Inceptisols of Bhubaneswar over 22 years revealed that continuous cultivation of rice without fertilizer ($N_0P_0K_0$) decreased grain yield by 52 % over initial year yield (9.7 q ha^{-1}) where as in N and NP treatments the grain yield was declined by 50 and 37%, respectively over the initial year yield (Fig. 4). With application of balanced NPK, the yield decline was narrowed down to 25%. Combined application of NPK+FYM and super optimal dose of NPK (150%) increased the grain yield by 21 and 10%, respectively over the initial year yield. With passage of time, the yield gap between control ($N_0P_0K_0$) and NPK+FYM treatment increased from 9 q ha^{-1} (initial year) to 25 q ha^{-1} over 41 cropping cycles. The decline trend was more prominent after 1983 onwards probably due to K and other micronutrients as limiting factors.

Fig. 4 Long term effect of nutrients on Rice yield (Kharif)



In acidic Inceptisols of Bhubaneswar, complete exclusion of K resulted in 74 % loss in yield and highest chaff production of hybrid rice (Table 8). A gradual increase in K rate increases grain yield, narrowed the grain: straw ratio and steadily improved the harvest index (Pattanayak et al. 2008).

Table 8 Effect of K rate on hybrid rice yield (two consecutive season) at Bhubaneswar

Treatments	Grain Yield (t ha^{-1})	Chaff (t ha^{-1})	Grain:straw ratio	Harvest Index
Control	8.0	1.00	1:1.44	0.39
25% K	9.3	0.90	1:1.29	0.42
50% K	10.7	0.80	1:1.15	0.45
75% K	11.2	0.70	1:1.15	0.45
100% K	13.9	0.48	1:1.01	0.49
CD (0.05)	0.5	0.08		

Source: Pattanayak et al. 2008

Benefit of use of Potassium on pulse was observed in the K deficient Balisahi series of Khurda district of Orissa (Mitra et al. 1993). Application of 40 kg K, 20 kg N and 40 kg P ha^{-1} to summer groundnut in laterite soils of Bhubaneswar significantly increased yield from 10.60 to 15.88 q ha^{-1}. Significantly higher yield (22.7 q ha^{-1}) of rabi groundnut over NP control (16.4 q ha^{-1}) with the application of 60 kg K ha^{-1} has also been reported. Results of farmer's field trials in alluvial soils of Siula (Puri district of Orissa) revealed that there was significant increase in green gram yield by 67% with application of 20 kg K ha^{-1} even without application of any N fertilizer (Mitra and Sahoo 1998).

Among the fruit crops, banana responded significantly to K application. At yield level of 58 t ha^{-1}, banana removes 1180 kg K ha^{-1}. Experimental results of OUAT revealed fruit yield, fruit weight, total soluble solids, total sugar and ascorbic acid content of banana increased with increasing level of K in alluvial soils of Puri district (Table 9).

Table 9 Effect of levels of K on yield and quality of banana in alluvial soil

K (g plant^{-1})	Yield (t ha^{-1})	Fruit weight(g)	Total soluble Solid	Total Sugar (%)	Ascorbic acid (mg/100 g pulp)
200	37.0	115.2	18.4	12.6	5.69
400	50.7	132.7	19.3	14.2	7.45
600	55.9	138.8	20.0	16.7	9.86
C.D.(0.05)	0.9	4.4	0.2	0.1	0.50

Source: Senapati and Santra 2009

The response of turmeric and ginger to K application is well documented. The data revealed that turmeric responded up to 90 kg K ha^{-1} and 26 % higher yield over K control (8.14 t ha^{-1}) was recorded. Similarly, the yield of ginger at 50 and 100 kg K ha^{-1} increased by 6 and 12% over control respectively. There was no response to higher dose of K.

Jena et al. (2006) reported that average response of rice to K application was of the magnitude of 7.8 kg per kg K_2O for mixed red and black, 4.8 to 6.4 kg for red and lateritic and 4.4 to 4.8 kg per kg of K_2O for mixed red and yellow soils where as there was no response to K application in coastal saline and brown forest soils. The average response of pulses (black gram and green gram) was of the order of 2.7 kg for brown forest soil and 4.4 kg for black soil per kg of K_2O applied. The variation in response in different soil groups could be attributed to difference in texture and mineralogy of soils.

Potassium removal and balances in different cropping systems

In rice-rice cropping system over 41 cropping cycles in laterite soil of Bhubaneswar, the K uptake under optimum fertilizer application (100% NPK) was 137 kg ha^{-1} which was increased to 167 kg ha^{-1} with integrated use of 100% NPK + FYM. The mean annual K balance was negative in all the treatments (Table 10). Green manuring or incorporation of paddy straw reduces K mining in rice-rice cropping system (Pal and Dash 2009). The K removal by rice – groundnut cropping system in alluvial soils was 180 kg ha^{-1} where as in rice – green gram cropping system in laterite soils it was 170 kg ha^{-1} (Jena 2008). In general, cereals, pulses and oil seed crops removes 226, 67 and 83 kg K ha^{-1}, respectively (Panda 1995). K removal in vegetables and fruit crops was much higher than cereals, pulses and oilseeds (Senapati and Santra 2009). The K removal by vegetables ranges between 90 to 480 kg ha^{-1}. Tuber crops like potato, cassava, sweet potato, elephant-foot yam remove about 310 to 350 kg K_2O ha^{-1}, whereas fruit crops like banana and pine apple remove 1180 and 530 kg K_2O ha^{-1}, respectively. In most of the cropping systems being practiced in India, potassium balance is negative (Rupa et al. 2003). A huge negative balance of 242.9 thousand tones of K in soils of Orissa has been reported by Misra and Mitra (2001) who suggested that dose of K for rice need to be revised from 30 to 60 kg ha^{-1} since 62% of K depletion is caused by rice.

Table 10 Mean annual K uptake and balance in some selected treatments under rice-rice cropping system (41 cropping cycles)

Treatments	Yield (q ha^{-1})		Mean Annual K Uptake (kg ha^{-1})	Mean Annual K Balance (kg ha^{-1})
	Kharif	Rabi		
Control	15.6	13.1	56.0	-56.0
100% N	20.9	20.5	84.0	-84.0
100% NP	22.5	28.0	90.0	-90.0
100% NPK	29.8	32.1	137.0	-37.0
100% NPK + FYM	34.8	37.6	167.0	-47.0
150% NPK	30.3	34.0	187.0	-7.0

Source: Sahoo 1994

Fig. 5 Nutrient balance of rice-groundnut cropping system in alluvial soils of Nimapara

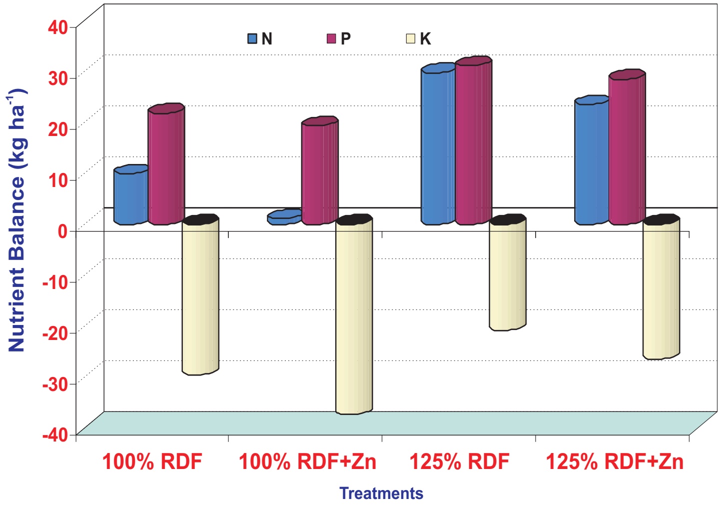
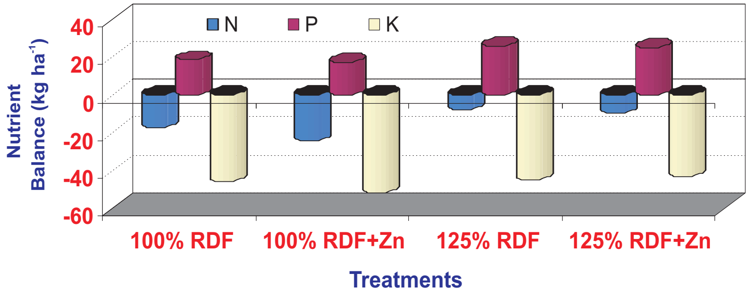


Fig. 6 Nutrient balance of rice-green gram cropping system in laterite soils of Nayagarh



The depletion of K to the extent of 51.0 and 37.0 kg ha^{-1} was recorded in rice – green gram and rice-groundnut cropping system, respectively at optimum level of K application (Jena 2008). However, at super-optimal level (150% NPK) the K depletion was decreased to 41.0 and 26.0 kg ha^{-1} in rice – green gram and rice-groundnut cropping system, respectively (Fig. 5, 6).

Management of potassium

Soil type, mineralogy, K fixation, amount and leaching loss of K should be considered while fixing the dose of K for different crops. Potassium fixation studies have revealed that soils become more hungry for K fixation with the continuation of negative balance. Illite soils fixed 23-29% of applied K, kaolinite and smectite soils 17-23% and 26-32%, respectively (Srinivas-Rao et al. 2000). Maintenance of shallow surface submergence in rice-rice cropping system in soils containing 2:1 clay minerals may increase K fixation and reduce solution K, thus increasing the rice dependence on non-exchangeable reserve for K uptake.

Leaching losses of K is a major concern under frequent intense rainfall conditions in well drained soils of humid tropics. Leaching tends to be a problem in soils with low CEC. The leaching losses of K in loam and sandy loam profiles under submerged moisture regime were 22 and 16% of applied K, respectively (Singh et al. 2004). Therefore, either K application level should be increased by 25-50% or the rice residues, which contain huge quantity of K (88-92% of total uptake), be recycled in the soil. Even burning of rice straw in field is a better option than its removal (Prasad 2007). Split application of K in the ratio of 1:1 at peak tillering and PI stage is recommended to rice to reduce the chaff percent and increase test weight.

Generally application of N, P_2O_5 and K_2O @ 20:40:40 kg ha^{-1} is recommended for groundnut in most of the soils of Orissa. Application of 40 kg K_2O ha^{-1} with NP to summer groundnut grown on the lateritic soils of Bhubaneswar significantly increased yield from 10.60 q ha^{-1} to 15.88 q ha^{-1}. Benefits of use of potassic fertilizers on pulses were also observed in the K deficient Balisahi series. Green gram yield was significantly increases due to application of 30 kg K_2O ha^{-1}. The recommended application (100% NPK) to rice – pulse and rice – oilseeds cropping system recorded highest yield and benefit:cost ratio. There was significant response to super optimal dose (150%) of NPK in alluvial and laterite soils having medium to high organic carbon status. Basal application of K @ 40 kg ha^{-1} at sowing is recommended for pulse crops in Orissa. Split application of K in the ratio of 1:1:1 at planting, 30 and 60 days after planting is recommended for vegetable crops like cabbage, cauliflower, brinjal, tomato and spices like chilli. Basal application of 30 kg K ha^{-1} for mustard and 60 kg K ha^{-1} for sunflower is recommended for higher yield and oil content. Integrated application of K with N, P and FYM improve the nutrient use efficiency and yield and hence recommended for higher profit.

Conclusion

The mining of K will limit crop yield and it may not be possible to maintain the present production. Results of long term fertilizer trials with rice-rice and rice-pulse cropping systems indicated that gradually the magnitude of response to applied K increased as K becomes limiting factor. Application of FYM, recycling of crop residues and green manuring can help to improve K balance in different cropping systems. Significant correlation of HNO_3-K with K balance and yield suggest its inclusion in soil testing laboratories. K balance in different cropping systems, based on precise data on K removal, K inputs from irrigation water or rain water, straw recycling besides fertilizers and manures needs to be worked out. Straw management can strongly influence K budget and can help in efficient management of K for a sustainable cropping systems in different regions. A sustainable fertilizer management strategy must ensure the farm productivity, optimum economic return without deterioration of agricultural environment.

References

Das PK, Sahu GC, Das N (1997) Vertical distribution and release characteristics of potassium in some lateritic soils of Orissa. J Potassium Res 13:105-110

Jena D (2008) Effect of optimal and super optimal level of NPK and micronutrient for enhancing production of rice based cropping system in Orissa. 14th IFFCO chair conference, 18-20 Sept.2008, Bhubaneswar pp.1-29

Katyal JC (2001) Fertilizer use situation in India. J Indian Soc Soil Sci 49:570-592

Kirk JGD, Begg CBM, Solivas JL (1993) The chemistry of the lowland rice rhizosphere. Plant Soil 1556, 83-86

Ladha JK, Dawe D, Pathak H, Padre AT, Yadav RL, Bijay-Singh (2003) How extensive are yield declines in long term rice-wheat experiments in Asia. Field Crops Res 81:159-180

Martin HW, Sparks DL (1985) On the behaviour of non exchangeable potassium in soils. Commun Soil Sci Plant Anal 16:133-162

Mishra KN (2008) Soil recourses mapping in Kanchinala micro-watershed under the coastal plain of Mahanadi Delta of Orissa. Ph.D. Thesis, OUAT, pp.1-176

Misra UK, Mitra GN (2001) Nutrient mining in agroclimatic zones of Orissa. Fertilizer News 46(4):73-79

Mitra GN, Sahoo D (1998) Nitrogen –potassium interaction on yield and quality development for rice-legume sequence in Orissa. Final Report. IPI-PRII sponsored research project, OUAT, pp.1-58

Nayak RK, Sahu GC, Nanda SSK (2001) Characterization, survey and classification of soils of Central Research Station, OUAT, Bhubaneswar. Agropedology 42 :1-8

Pal AK, Pattnaik MR, Santra GH, Swain N (2001) Studies on K releasing power of laterite soils of Cuttack district. J Indian Soc Soil Sci 49:70-74

Pal AK, Dash AK (2009) Potassium balance and release characteristics under rice-rice cropping system. State level seminar on "Optimising crop production through judicious use of potassium", 28 May 2009, OUAT, Bhubaneswar

Panda N (1995) Balanced fertilization use for increasing food grain production in eastern states. Proc. of Zonal Symposium held at OUAT, Bhubaneswar PPIC-India Programme, pp 5-21

Parker DR, Hendricks GJ, Sparks DL (1989b) Potassium in Atlantic Coastal plain soils: II. Crop responses and changes in soil potassium under intensive management. Soil Sci Soc Am J 53:397-401

Pattanayak SK (1992) Effect of long term fertilizer and manure application to a medium land acid laterite on nutrient transformation and changes in some soil properties, Ph.D. Thesis, IARI, New Delhi

Pattanayak SK, Mukhi SK, Majumdar K (2008) Potassium unlocks the potential for hybrid rice (India) Better Crops with Plant Food 92(2):8-9

Prasad R (2007) Primary and secondary nutrient uptake pattern by rice as a guide to fertilizer application practices. Indian Farming June-2007:5-8

Rupa TR, Srivastava S, Swarup A, Sahoo D, Tembhare BR (2003) The availability of potassium in Aeric Haplaquepts and Typic Haplusterts as affected by long term cropping, fertilization and manuring. Nutr Cycl Agroeco 65:1-11

Sahu GC, Panigrahi SK, Nayak N (1995) Characterization, classification and land use planning of the soils of a watershed in the Eastern Ghat region of Orissa. J Curr Agril Res 8:21-26

Sahu GC, Panda N, Nanda SSK (1983) Genesis and mineralogy of some red and laterite soils of Orissa. J Indian Soc Soil Sci 31:254-262

Sahu GC, Patnaik SN, Das PK (1990) Morphology, genesis, mineralogy and classification of soils of northern plateau zone of Orissa. J Indian Soc Soil Sci 38:116-121

Sahu PK (1994) Distribution of different forms of potassium and its release pattern in rice growing soils of Athagarh. M.Sc. (Ag) Thesis, OUAT, pp. 1-93

Sekhon GS, Brar MS, Subba-Rao A (1992) Potassium in some Benchmark soils of India. PRII Spec. Pub.3, Potash Research institute of India, Gurgaon, Haryana, India. p.82

Senapati AK (1993) Long term effect of fertilizer on release pattern of K in a lateritic Inceptisol under rice-rice system. M. Sc. (Ag) Thesis, OUAT, Bhubaneswar pp. 1-24

Senapati HK, Santra GH (2009) Potassium management in vegetables, spices and fruit crops, state level seminar on "Optimising crop production through judicious use of potassium", 28 May 2009, OUAT, Bhubaneswar

Singh M, Singh VP, Damodar-Reddy D (2002b) Potassium balance and release kinetics under continuous rice-wheat cropping system in Vertisols. Field Crops Res 77:81-91

Singh Y, Singh B, Ladha J K, Khind CS, Gupta RK., Meelu OP, Pasuquin E (2004) Long-term effects of organic inputs on yield and soil fertility in the rice-wheat rotation. Soil Sci Soc Am J 69:845-853

Spark DL (2000) Bioavailability of soil potassium, D-38-D-52. In Summer ME (ed.) Handbook of soil science. CRC, Boca Raton, Florida

Srinivas-Rao Ch, Rupa TR, Subba-Rao A, Bansal SK (2000) Potassium fixation characteristics of major Benchmark soils of India. J Indian Soc Soil Sci 48:220-228

Wihandjaka AG, Kirk GJD, Mantauk CP (1999) Potassium balance in rainfed low land rice on a light textured soil. Field Crops Res 64:237-247

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Quantifying uptake rate of potassium from soil in a long-term grass rotation experiment

I Öborn • A C Edwards • S Hillier

Abstract Soil-plant potassium (K) dynamics were studied using a long-term field experiment in order to evaluate the plant performance and K delivering capacity of the soil parent material. Rye grass (*Lolium perenne* L.) based rotations on a loamy sand derived from granitic bedrock were studied over 30 years with two K-fertilisation regimes, nil (K0) and 65 kg K ha^{-1} yr^{-1}. Mineralogical and chemical methods were combined to identify and quantify soil K resources including the partitioning of K between minerals. Two or three cuts were taken annually and herbage yield and composition together with exchangeable soil K were analysed. Herbage yield declined with time and significantly reduced when the K concentrations approached 1%. The grass K concentration also declined over time and stabilized at around 0.5-0.7% (dw) in K0 in all cuts. Input-output mass balances showed an accumulated net K off-take (deficit) of 1100 kg ha^{-1}, i.e. 35 kg ha^{-1}yr^{-1}. With an exchangeable K pool of 100 kg ha^{-1} (in the rooting zone 0-40 cm) this indicated a substantial release of K from mineral sources, most probably biotite and hydrobiotite. Assuming a similar net off-take was continued then this particular mineralogical K source would be depleted within two centuries. The study illustrates the strength of combining long-term field experimental data with state of the art quantitative mineralogical methods in order to assess site-specific resources which can form a basis to evaluate the sustainability of different management practices.

Keywords Depletion • perennial ryegrass • potassium release • soil minerals weathering

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Introduction

Nutrient imbalances are a common feature of many agricultural systems, with both annual surpluses and deficiencies being reported (e.g. Smaling et al. 1999; Askegaard et al. 2004). While much emphasis has been given to quantifying nitrogen (N) and phosphorus (P) balances at geographical scales ranging from field to nation, similar calculations are not generally reported for potassium (K). One notable exception is Foy et al. (2002). A lack of any obvious environmental concerns associated with a K surplus is probably the main factor responsible for this omission. This general situation is changing due to factors such as the increased price of agricultural inputs including K fertilisers. Evidence for a decline in soil K status has been provided through the regular monitoring of agricultural soils in England and Wales (Goulding and Loveland 1986; Skinner and Todd 1998) where both regional and temporal trends in soil extractable K were described for the previous 25 years. There was some indication for a wider decline in K status, particularly evident for grassland, with 20% of all fields sampled in the Northern region having a low K status (index 0). Declining rates of K fertiliser coupled with manure applications determined on the basis of their N content has resulted in a wide ranging annual K balance within cropping systems of NW Europe (e.g. Askegaard and Eriksen 2002; Alfaro et al. 2003; Berry et al. 2003; Kayser and Isselstein 2005; Öborn et al. 2005a, b). Also in other geographical regions negative K balances in agricultural production systems have been reported urging for intensified research efforts on K management and dynamics in different soil types, climatic regions and cropping systems (e.g. Bedrossian and Singh 2004; Bell et al 2009). Greatly increased crop yields and nutrient off-take in harvested products have exacerbated this situation. Losses of K can also be associated with home produced forage crops and recycling of manure/urine (e.g. Öborn et al. 2005b; Gustafson et al. 2007), and/or where excessive leaching occurs from coarse textured soils (e.g. Wulff et al. 1998; Askegaard and Eriksen 2008). Within systems managed organically negative K field balances have also been reported (e.g. Watson et al. 2002; Askegaard et al. 2003; Bengtsson et al. 2003), and there is a growing concern about net off-take of K and how to sustain the soil fertility, harvest level and crop quality (e.g. Fortune et al. 2005). Export of nutrients accompanies the sale of all agricultural produce and inherent site-specific soil properties such as mineralogy and texture coupled with climatic factors and farming system determine the likely long-term significance of any potential K deficiency (e.g. Heming 2004; Andrist-Rangel et al. 2007; Simonsson et al. 2007; Barré et al. 2008; 2009).

The significant contribution that soil minerals can make to plant available K means that this aspect should also be considered in addition to fertiliser and manure inputs. While lack of total soil K (Tot-K) reserves (organic soils being an exception) is not often an issue, it is possible that short-term deficits of plant available K, for example, during the later part of the pasture growing season may occur (e.g. Brady and Weil 1996). During these times the rates of exchange between various soil K sources need to be considered. Various soil K pools have been defined as, soil solution K, exchangeable K, fixed or non-exchangeable K bound in the inter-layer positions, e.g. of weathered micas, vermiculites etc., and finally structural K particularly associated with micas and K-feldspars (e.g. Sparks and Huang 1985; Sparks 1987; Huang 1989; Robert 1992). The dynamic situation that exists between the K pools determines the plant available K and is among other things influenced by plant properties such as root density and rooting depth (e.g. Haak 1981; Kuhlmann 1990; Witter and Johansson 2001), climatic conditions (soil temperature and moisture) (e.g. Holmqvist et al. 2003), soil attributes (organic acids, pH, particle size distribution etc) as well as type of K bearing minerals (e.g. Wilson 1992; 2004; Hinsinger and Jaillard 1993; Barré et al. 2007; 2008) and management practices (e.g. Singh and Goulding 1997; Simonsson et al. 2007).

This paper describes the long-term soil-plant K dynamics for a grass (*Lolium perenne* L.) based rotation growing on a loamy sand soil derived from granitic bedrock. Treatments without or with annual fertiliser K additions are compared over a 30 year period and the system sustainability including the plant performance and K delivering capacity of the soil parent material are considered. It was hypothesised that K-bearing soil minerals could supply sufficient K to maintain grass herbage production in low input systems.

The specific objectives were to:

i) Assess the annual and within year performance of herbage biomass production and K concentration of ryegrass herbage;
ii) Establish annual and long-term K input-output mass balances in order to identify major sources and sinks and assess temporal trends;
iii) Study trends in plant available (acetic acid extractable) K, and
iv) Quantify individual chemical and mineralogical soil K pools in order to determine their potential contributions to long-term plant available K.

Materials and Methods

Site and soil description

The experimental site was located on Macaulay Institute grounds at Craigiebuckler (57° 8'N, 2° 9'W), Aberdeen, NE Scotland. The mean annual average temperature and rainfall were 7.9° C and 791 mm, respectively (1961-80; Dyce airport 57° 12'N, 2° 12'W) (Broad and Hough 1993). Precipitation was measured on the experimental site 1968-95 and the monthly averages were used when evaluating the uptake rates. The average growing season (6° C) in the area was 215 days (s.d. 14 days) lasting from 8 April to 10 November (Broad and Hough 1993).

The soil was classified as Dystric Cambisol (FAO) or Typic Fragiorthod (Soil Taxonomy) (Adamo et al. 1998). According to Scottish terminology it is a freely draining iron humus podsol developed in glacial till derived from granitic bedrock and it belongs to the Countesswells Association and Dess Series (Glentworth and Muir 1963). Soil and profile characteristics of the experimental site are given in Table 1.

Experimental design

The field experiment was established in 1968 and had a randomised block design with two K treatments, K65 which received 65 kg K ha^{-1} yr^{-1} (as KCl) and K0 which received no K, and five replicates. Three experimental phases could be defined; an initial 12 year period of grass (Grass I, two cuts per year) followed by 6 years with cereals (Cereal), and a final 11 years of grass (Grass II, three cuts per year). The timing of the cuts, i.e. the growth stage of the grass, was set to mimic the hay/silage cuts by farmers. During the two grass periods the K65 plots received fertiliser annually during the spring. All plots also received a basal N (50 kg N ha^{-1}yr^{-1}) dressing as nitrochalk at the start of the growing season and after each cut, i.e. in total 100 kg N ha^{-1} yr^{-1} for Grass I and 150 kg N ha^{-1} yr^{-1} for Grass II. During the six-year cereal period a similar annual basal N, P and K dressing was applied to all plots (75-85 kg N, 19-21 kg P and 63-74 kg K). The cropping sequence therefore consisted of perennial ryegrass (*Lolium perenne* L.) established in 1969 (Grass I) and 1987/88 (Grass II) with the cereal phase consisting of four years of spring barley (*Hordeum vulgare,* L.), one year of oats (*Avena sativa* L.), and one year of winter wheat (*Triticum aestivum,* L.).

Sampling and sample treatment

Responsibility for sample collection and analysis changed over the 30 year experimental period, however, protocols were all well documented and analytical data consistently recorded.

Plant sampling and preparation

Total herbage biomass yield was recorded at each cut, and a sub-sample taken for dry matter determination and chemical analyses. All remaining herbage was removed from the field to simulate a hay/silage situation. Prior to digestion and chemical analyses herbage samples were dried at 60° C and milled. For cereals, the grain weight was recorded and sub-samples taken and prepared for analysis. Both

Table 1 Characterisation of the soil profile at the experimental field. The data are for composite samples from the 10 plots. Bulk density, g cm^{-3}, was determined for the <2mm fraction[c]. Exchangeable (Ex) cations and CEC(pH 7)[5] are given in cmol(+) kg^{-1}dw. The particle size fractions[3] (%) are given as clay (<2m), silt (2-60m) and sand (60m -2mm). Relative root distribution (%) is from Edwards et al. (1987).

Hori-zon	Depth cm	pH[a] CaCl[2]	C[b] %	N[b] %	S[b] %	Bulk den-sity[c]	Cl[d]	Si[d]	Sa[d]	Ca[e]	Mg[e]	K[e]	Na[e]	CEC[f]	BS[g] %	Rel root distr.
Ap1	0- 5	4.9	5.4	0.38	0.04	0.71	2	17	81	8.1	0.8	0.2	0.3	19	50	42
Ap2	5-15	5.1	4.3	0.30	0.04	0.65	1	17	82	8.2	0.3	0.1	0.1	17	51	21
Ap3	15-25	5.2	4.1	0.28	0.02	0.80	2	22	76	9.6	0.1	0.1	0.1	17	58	21
Bs	25-40	5.2	1.5	0.09	0.01	0.68	4	21	75	4.1	0.1	0.1	0.1	9	48	16
BC	40-60	5.3	-	-	-	0.73	7	25	68	5.2	0.1	0.1	0.1	10	52	~0

[a] Soil pH in 0.01 M CaCl$_2$, soil:solution ratio 1:2; [b] Total-C, -N and -S (weight %) – finely ground soil was analysed on a Leco; [c] The soil is formed in glacial till where gravels and stones were abundant (>2mm) and thus the bulk density for the <2mm was low; [d] Pipette method, samples dispersed in deionized water with ultrasonic probe; [e] 10 g soil 250 ml 1M NH$_4$Ac (pH 7) (Rowell 1994), Ex-Ca, Ex-Mg, Ex-K and Ex-Na analysed by ICP-AES. [f] CEC$_{pH\ 7}$ = sum of Ex-cations (Ca^{2+}, Mg^{2+}, K$^+$, Na$^+$) and acidity. Acidity: mix 5 g soil with 1M Ba-acetate (pH 7) and titrate with Ba(OH)$_2$ to pH 7. [g] Base saturation (BS) = (Ex-cations/CEC$_{pH7}$)*100.

the cereal grain and the straw were removed from the field, and in 1987 straw was sampled and analysed. For budget calculations the straw weight was estimated using a grain:straw ratio of 1:1 (Hanson 1990). In two years, 1981 (grass) and 1985 (barley), the plots were cut and cleared but no yield recorded, on these occasions the average K removal from grass 1978-80, and barley 1982 and 84, were used in budget calculations as estimates for 1981 (grass) and 1985 (barley), respectively.

Soil sampling and sample preparation

Surface soil (0-15 cm) was collected annually in the autumn (after the last herbage cut) 1968 to 1987 when approximately 10 sub-samples were taken from each plot with a screw auger. In April 1998 (before the fertilisation), soil samples were taken from three surface horizons, 0-5 cm (Ap1), 5-15 (Ap2) and 15-25 cm (Ap3), and one subsurface horizon within the rooting depth (B, 25-40 cm). When possible (only in 5 plots because it was very stony), the BC-horizon (40-60 cm) was sampled. Within each plot 20, 10, 10 and 5 sub-samples were taken from 0-5 cm, 5-15, 15-25 cm, and 25-40 cm depths respectively. A core sampler was used for the 0-25 cm samples and a screw auger for the 25-60 cm depth. The C-horizon (60-80 cm) was also sampled in three soil pits located immediately adjacent to the experimental plots. In total 0.5-1 kg soil per plot and horizon was taken. The soil was sieved fresh at 2 mm and air-dried at 30° C prior to the analyses. The mineralogical analyses were carried out on pooled composite samples from the different horizons.

Soil bulk density

The bulk density for each soil horizon was determined in the three soil pits (0.5*0.5*0.5 m). All soil from each horizon was removed, and the volume of the removed horizon was carefully measured in the soil pit. The soil was air dried, sieved and the <2mm fraction weighed and its bulk density calculated for each horizon. The average values from the three profiles (Table 1) were used in the calculation and expression of soil K data on an aerial basis.

Plant and soil analyses

Plant analyses

The crop samples were wet-digested and K was analysed by flame photometry (1969-88) or ICP-AES (1989-1998). The straw K concentration measured in 1987 in the K0 and K65 treatments, respectively, were used as general estimates for the straw K concentration in the two treatments. The weighted annual average K concentrations were calculated for the grass cuts and used in graphs and budget calculations.

Soil analyses

Acetic acid extractable-K (Ac-K) was determined annually on soil collected from individual plots between 1969 and 1987, and then in 1990, 1991 and in 1998. Air-dried soil (2.5 g) was extracted by 100 ml 2.5% acetic acid (MISR/SAC 1985) and K was analysed by flame photometry (1969-88) or ICP-AES (1988-1998). In addition, a subset of samples (n=10) were extracted with 1 M ammonium acetate (NH_4Ac pH 7) (Rowell 1994) and analysed by ICP-AES in order to relate the Ac-K extraction to an internationally frequently used extraction for exchangeable K. Acetic acid (2.5%) extracted on average 94% of 1 M NH_4Ac and Ac-K will in this paper be used as a proxy for exchangeable K. Aqua-regia K (Aq-K) was extracted by 3:1 50% HCl:conc. HNO_3 (by volume) (McGrath and Cunliffe 1985; McGrath 1987) and analysed by ICP-AES. Total-K (Tot-K) was determined by X-ray fluorescence (XRF) using a Philips PW 1404 spectrometer and the methods by Norrish and Hutton (1969) for sample fusion and corrections for interelement effects.

For determination of the mineralogical composition 3 g soil (<2 mm) was ground in an agate McCrone mill for 12 min with 9 g of liquid (0.5% polyvinyl alcohol and 2 drops of octanol) and spray dried as per Hillier (1999). X-ray powder diffraction (XRPD) patterns were recorded on a Siemens D5000 instrument from 2-75°2θ using Cobalt Kα radiation, in 0.02° steps counting for 2 seconds per step. The resulting XRPD patterns were quantified by full-pattern fitting as described in detail by Omotoso et al. (2006, participant 18). Uncertainty at 95% confidence is given by $X^{0.35}$, where X is concentration in weight percent (Hillier 2003). Mineralogical analyses were carried out on composite samples from the experimental plots. The partitioning of K amongst the identified mineral phases was estimated using assumed chemical compositions (Table 2) (Andrist-Rangel et al. 2006; Andrist-Rangel 2008).

Table 2 K-bearing mineral phases and their assumed elemental composition used in the normative calculations

Mineral phase	Elemental composition
K-feldspar	$KAlSi_3O_8$
Muscovite	$KAl_2(AlSi_3O_{10})(OH)_2$
Illite	$K_{0.6}Al_{2.15}Mg_{0.3}Fe^{III}_{0.22}Ca_{0.05}Na_{0.03}Si_{3.4}O_{10}(OH)_2$
Biotite	$KMg_{1.5}Fe^{II}_{1.5}AlSi_3O_{10}(OH)_2$
Hydrobiotite	$K_{0.5}Mg_{1.5}Fe^{II}_{1.0}Fe^{III}_{0.5}AlSi_3O_{10}(OH)_2$

K input-output mass balance calculations

Input-output mass balance for K was calculated for the two K treatments (Equation 1). The inputs taken into account were K-fertiliser ($Fert_K$) application and atmospheric deposition (Dep_K), and the outputs were K removed by harvest products ($Crop_K$) and leaching ($Leach_K$). A K-surplus indicates a net accumulation of K in the soil pool ($Soil_k$), whereas a K-deficit means that $Soil_K$ is decreasing.

$$\Delta Soil_K = Fert_K + Dep_K - Crop_K - Leach_K \qquad \text{(Eq. 1)}$$

Dep_K was estimated from an average rain water concentration of 5µg L^{-1} measured by Reid et al. (1981) and the mean annual precipitation for 1961-80. The run-off was calculated from mean monthly data on precipitation and evapotranspiration (1961-80). Soil water K concentrations were obtained from an adjacent field experiment, and $Leach_K$ estimated from mean monthly run-off data and soil-water K concentrations.

Estimation of K 'uptake rate' and K uptake within the rooting zone

The K 'uptake rate' (kg K ha^{-1} d^{-1}) was roughly estimated by dividing the grass K removal by each cut by the days between the cuts. For cut 1, the days from 1 April to the harvest time was used as estimate for the growth period. For cut 2 and cut 3 the days elapsed between the grass cuts was used.

The root length density (cm cm^{-3}) from an established grass sward on an adjacent field with the same soil type was used to estimate the K uptake from different soil depths (Edwards et al. 1987). Edwards et al. (1987) determined the root length density using soil cores subdivided into the depths; 0-5, 5-15, 15-25(/30) cm (subsoil boundary) and subsoil (30-45 cm). The root length density was highest in the upper 0-5 cm where it was 25-30 cm cm^{-3}. The main part of the roots, 42%, were found in the upper 0-5 cm, 21% in each of the 5-15 and 15-25 cm layers, respectively (Table 1).

Statistical analyses

The statistical analyses were carried out using SYSTAT for Windows 8.0 (Systat 1998) and EXCEL (Microsoft Excel 2002). Analysis of variance (ANOVA) was carried out using the GLM procedure followed by the Tukey test for pair-wise comparison of means. We considered statistical probabilities of $p<0.05$ as significant.

Results

Grass biomass production and K concentrations

Herbage yield

Highest yields, >10 tonnes dw ha^{-1} (t ha^{-1}) occurred during the first few years of Grass I, with both treatments displaying a trend of declining production. Yields remained comparable between treatments for the first five years after establishment. The yield for K0 continued to decline until an apparent plateau at about 6 t ha^{-1} was reached, and from the seventh year the K65 plots had a significantly higher production (Fig. 1a). After the break years with cereals no significant differences in biomass harvest for the first two years of Grass II were apparent, but from the third year until the end of the period the K65 plots showed a significantly higher yield (Fig. 1a). The accumulated herbage yield over the two

Fig. 1 Annual (a) biomass yield (tonnes dry weight (dw) ha^{-1}), (b) potassium (K) concentration (% dw) in the grass herbage given as weighted mean for the cuts , (c) K removal by crop off-take (kg K ha^{-1}), and (d) net off-take of K (Input via K-fertiliser – Output via harvested biomass, kg K ha^{-1}), in the K0 (▲) and K65 (□) treatments in the field experiment. Bars represent the standard error calculated from 5 replicates, with only one side shown for clarity. The dotted vertical lines indicate the three experimental phases; Grass I, Cereals and Grass II.

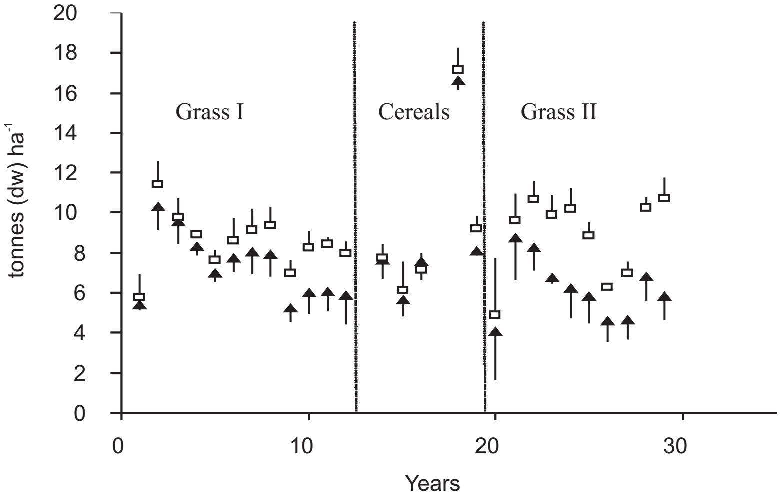


Figure 1a

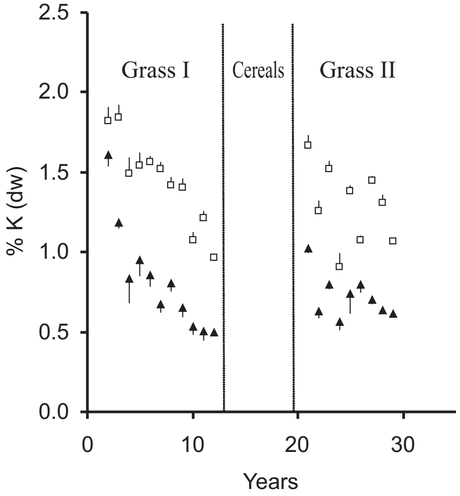


Figure 1b

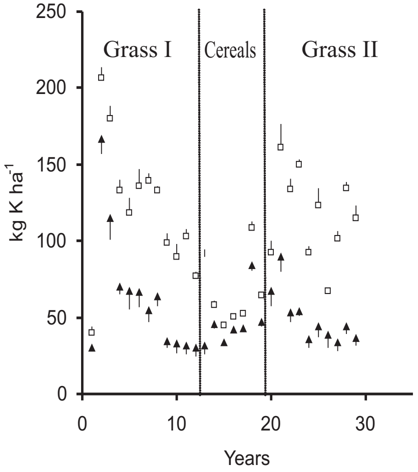


Figure 1c

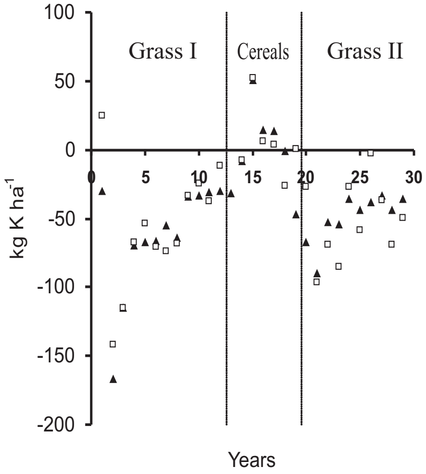


Figure 1d

grass phases was 140 and 180 t ha^{-1} for K0 and K65, respectively, or 7 and 9 t ha^{-1} yr^{-1} if expressed on average annual bases.

Herbage K concentrations

The annually averaged herbage K concentration decreased significantly in K0 and K65 treatments during both Grass I and II periods (Fig. 1b). The K65 herbage had a K concentration of 1.7% initially, and thereafter it steadily declined to 1.1% by the end of Grass I. In K0 the K concentrations were always less than those in the comparable K65 material, declining rapidly to <1.0% and finally reaching 0.5% for the last 3 years of Grass I. During Grass II, the initial K concentration was 1.5 and 0.8% for K65 and K0, respectively, and by the end of this grass period it had reached 1.3 and 0.6%, respectively. The difference in K concentration between the K65 and K0 treatments was statistically significant during the entire period the plots were under grass.

K dynamics during the growing season

For the Grass II phase, data for individual cuts on biomass harvests and herbage K concentration were further analysed (Table 3). The first cut (cut 1) accounted for the major biomass yield, being roughly double that of cut 2 and three times larger than cut 3 (Table 3).

Table 3 Biomass harvest and K concentration (per unit dry weight, dw) in grass the three annual cuts from the second grass period (Grass II). The K removal by harvest (biomass*K concentration) was recalculated as 'uptake' rate based on the days of growth[a]. Means and standard errors (within brackets) are given (n=5)

Treatment	Cut	Biomass harvest tonnes (dw) ha^{-1}	K conc in grass % (dw)	K 'uptake' rate kg ha^{-1} d^{-1}
K0	1	3.66 (0.38)	0.74 (0.06)	0.40 (0.06)
	2	1.79 (0.14)	0.71 (0.05)	0.26 (0.04)
	3	1.24 (0.14)	0.75 (0.05)	0.14 (0.02)
K65	1	5.45 (0.54)	1.48 (0.12)	1.15 (0.10)
	2	2.54 (0.12)	1.12 (0.04)	0.57 (0.07)
	3	1.66 (0.20)	1.00 (0.07)	0.24 (0.03)

[a] April 1 was used as an estimate of the start of the growing season for cut 1

The K65 treatment had overall a higher yield than the K0, the difference being most pronounced for cut 1. In the K65 treatment, herbage K concentration was highest (1.5%) in cut 1, decreasing to 1.1 and 1.0 % in cut 2 and 3, respectively (Table 3). Herbage K concentration was low (0.7 %) in K0 and remained similar throughout the growing season. An estimate of daily K 'uptake rate' was calculated for individual cuts and it declined substantially from the first to the third cut in both K65 and K0 (Table 3). The uptake rate of K was always greater for K65 than K0 and the decline was larger in K65 as compared to K0. The K uptake rate was not significantly related (with simple linear regression) to the accumulated precipitation during the growth period (roughly April-May for cut 1, June-July for cut 2 and August-September for cut 3) (data not shown).

Potassium off-take and K input-output mass balances

Annual K removal and net off-take by biomass harvest

The total amount of K removed annually in the harvested biomass declined with time but was always significantly greater for any given year in the K65 treatment compared to the K0 treatment (Fig. 1c). The annual net K off-take was calculated as the fertiliser derived input minus the K removed in harvested biomass (Fig. 1d). During the first two years of Grass I the deficit was large, being more than 100 kg K ha^{-1} yr^{-1} (Fig. 1d). Thereafter crop removal exceeded fertiliser application by 55-70 kg K ha^{-1} yr^{-1} during a five year period, followed by four years with a smaller net K off-take of around 30 kg ha^{-1} yr^{-1}. There was generally no significant difference in net off-take between the K0 and K65 plots during Grass I. Grass II showed a similar pattern with a net off-take between 90 and 100 kg K ha^{-1} yr^{-1} the first year, thereafter 55-85 kg ha^{-1} yr^{-1} for two years, and 40 kg ha^{-1} yr^{-1} during the final years (Fig. 1d). There was no significant difference in net off-take between K0 and K65 for six years of Grass II.

Input-output K mass balances

The input-output mass balance calculations for the entire period showed an annual K deficit during the two grass periods (Grass I and Grass II) and a surplus during the 6-years of cereals (Table 4). During Grass I, an average of 67 kg K ha^{-1} yr^{-1} was removed by herbage from the K0 plots whereas 128 kg K ha^{-1} yr^{-1} was removed from the K65 plots. This resulted in K removal in the herbage greatly exceeding the amount added as fertiliser and resulted in an annual deficit of about 65 kg K ha^{-1}, a value that was similar for both treatments. During Grass II the annual K removal by herbage averaged 48 and 120 kg K ha^{-1} for the K0 and K65 treatments, respectively, and the K mass balance calculation showed an average deficit of 47 (K0) and 56 (K65) kg K ha^{-1} yr^{-1}. The cereal crops all received K fertiliser, on average 63 (K0) and 73 (K65) kg K $ha^{-1}yr^{-1}$, and during that period the annual K surplus was 15 (K0) and 10 (K65) kg K ha^{-1} yr^{-1} (Table 4).

Acetic acid extractable soil K and its turnover rates

Acetic acid extractable soil K

At the start of the experiment the K status of the soil was moderate to low and over time it dropped into very low status (MISR/SAC, 1985). The long-term dynamics of Ac-K in the surface soil (0-15 cm) showed an annual variation but also a clear difference between the years with grass compared to those with cereals, the Ac-K concentration being lower under grass (Fig. 2). The general trend was similar for both treatments, but the K0 plots overall showed a lower Ac-K than the K65 plots. A very dry summer could be a possible explanation for the high Ac-K concentrations recorded by the end of the 6th year of Grass I (1976). Ac-K was only determined on three occasions during Grass II, with the final sampling taking place in spring, and although based on very few observations the concentrations appeared to be at similar (or lower) levels to those measured during the Grass I phase.

Table 4 Annual K mass balances, kg K ha^{-1} yr^{-1}, for the three periods: (i) 11 years of grass (Grass I, 1970-80), (ii) 6 years of cereals (Cereals, 1982-87), and (iii) 9 years of grass (Grass II, 1989-97). The years when the rye grass was established were not included (1969, 1988)

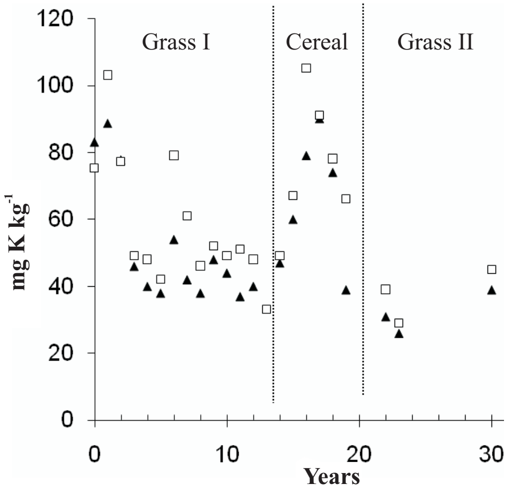
Treatment	Inputs Deposition	K-fertiliser	Outputs Leaching	Harvest	Inputs-Outputs Deficit/Surplus
Grass I					
K0	1.4	0.0	0.8	66.6	-66.0
K65	1.4	65.0	2.3	128.4	-64.3
Cereals					
K0[a]	1.4	62.6	0.8	47.8	+15.4
K65[a]	1.4	73.5	2.3	62.9	+ 9.7
Grass II					
K0	1.4	0.0	0.8	47.7	-47.0
K65	1.4	65.0	2.3	119.9	-55.7

[a] During the period with cereals a basal NPK dressing was applied, except for 1987 when the 0 and 65 kg K treatments were applied

Soil K turnover rates

The replenishment of the Ac-K pool in the topsoil (0-15 cm) was estimated for Grass I where annual data for net off-take (Fig. 1d) and Ac-K (Fig. 2) were available. Replenishment was estimated based on two different assumptions (Fig. 3); (1) all K (100%) in herbage was taken up in the top 15 cm, or (2) K was taken up proportional to the root distribution (Table 1), i.e. 63% in top 15 cm. With the first assumption, after the initial two years, the net K off-take was about double the amount of the Ac-K for the following 5 year period, i.e. the ratio was around 2 during this time, indicating that the Ac-K pool was replenished twice a year (Fig. 3). The K0 was replenished somewhat quicker than K65, i.e. the ratio was 2.3 (K0) and 1.8 (K65). During the final 4 years, the net K off-take was of a similar quantity as the Ac-K pool, i.e. the ratio was close to 1 (K0 1.1 and K65 0.8), indicating that the Ac-K pool was replenished once per year (Fig. 3). For the second assumption

Fig. 2 Acetic acid extractable K (Ac-K, mg K kg^{-1} soil) in the Ap-horizon (0-15 cm) determined annually during the first 18 years (1969-1987) and by the end of the experimental period (1998) in the K0 (▲) and K65 (□) treatments. The dotted vertical lines indicate the three experimental phases; Grass I, Cereals and Grass II.



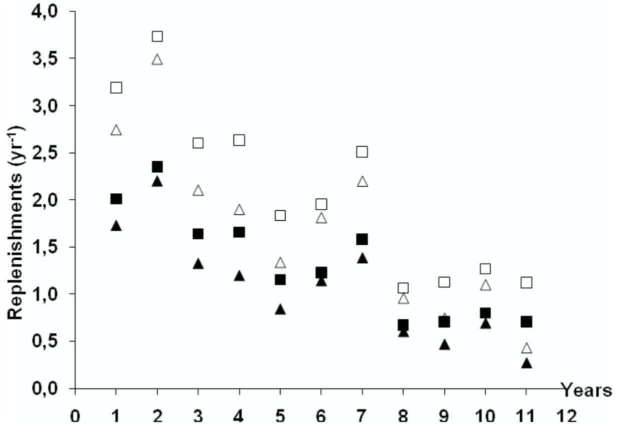
and the same time periods the ratio was lower, 1.4 (K0) and 1.1 (K65) for years 2-7, and 0.7 (K0) and 0.5 (K65) for years 8-11, showing that the Ac K pool was initially replenished in less than a year and thereafter took between 1.5 and 2 years to replenish (Fig. 3).

Soil K resources and their relative contributions to plant available K

Potassium in the soil profile (rooting zone)

The distribution of K within the soil profile (rooting zone) of the K0 and K65 plots was determined 30 years after the start of the experiment and included the measurement of three K fractions; Tot-K, Aq-K and Ac-K (Table 5). Potassium concentrations were compared within profiles as well as between the K0 and K65 treatments. Tot-K concentration was significantly higher in the B and BC horizons as compared to the Ap horizons (Table 5). A similar pattern was apparent for Aq-K. Ac-K was significantly higher in both Ap1 horizons compared to other soil horizons, and it was higher in the K65 treatment as compared to the K0 (Table 5). The Aq-K fraction represented 16-20% of Tot-K in the Ap and Bs horizons whereas it accounted for 30% in the BC horizon.

Fig. 3 The replenishment of the Ac-K pool in the 0-15 cm layer during Grass I calculated as: Replenishments (yr^{-1}) = Net K-off take (kg ha^{-1} yr^{-1})/Ac-K pool (kg ha^{-1}) in the K0 (▲, Δ) and K65 (■, □) treatments. The filled symbols are showing the replenishment assuming that 63% of K is taken up from the 0-15 cm horizon (related to the relative root distribution) and the open symbols are based on 100% K uptake from the top 15 cm.



The quantities of K within the various extractable fractions were calculated for the horizons of the K0 and K65 soil profiles. The Aq-K and Tot-K soil pools in the main rooting zone (0-40 cm) approximated 13 000 and 72 000 kg K ha^{-1}, respectively (Table 6). The corresponding Ac-K pool was 98 and 106 kg K ha^{-1} in the K0 and K65 treatments, respectively.

Soil mineralogical composition and partitioning of total K in the solid phase

The quantitative XRPD analyses showed that about 30% of the soil minerals contained K, and these minerals were partitioned one third as K-feldspar and two thirds as 2:1 phyllosilicates (Table 7). The dioctahedral micas, muscovite and illite, were the main phyllosilicates (12-15%), but there were also considerable amounts (5-9%) of trioctahedral mica (biotite) and hydrobiotite, a common weathering product of biotite.

The partitioning of K amongst the identified mineral phases showed that on average 55% of the K was allocated in the form of K-feldspar, 32% in dioctahedral phyllosilicates and 12% in trioctahedral biotite and hydrobiotite. The results also show that there was more K held in micas in the Bs- and B/C-horizons as compared to the surface layers (Ap1-Ap3), and this was especially evident with respect to the trioctahedral mica minerals biotite and hydrobiotite (Table 8).

Table 5 Soil K concentrations in the K0 and K65 treatments 30-years after the start of the experiment. Total K (Tot-K, < 2 mm), aqua regia extractable K (Aq-K, < 2 mm) and acetic acid extractable K (Ac-K, < 2 mm) were determined and the ratio between Aq-K and Tot-K were calculated; (Aq-K/Tot-K)*100. Means of 5 plots and standard deviations (within brackets) are given for Tot-K and Ac-K. Values having the same letter suffix do not differ significantly ($p < 0.05$)

Treatment/ Horizon	Depth, cm	Tot-K g kg^{-1}	Aq-K^{a} g kg^{-1}	Ac-K mg kg^{-1}	Aq-K/ Tot-K %
K0					
Ap1	0- 5	22.9^{a} (0.5)	3.74	53.0^{b} (1.5)	16
Ap2	5-15	23.9^{b} (0.6)	3.86	32.7^{c} (5.1)	16
Ap3	15-25	24.3^{b} (0.5)	4.35	30.3^{c} (2.4)	18
Bs	25-40	27.4^{c} (0.8)	5.39	33.0^{c} (9.6)	20
BC^{b}	40-60	28.5	6.76	41.9	30
C^{b}	60-80	nd	5.95	nd	nd
K65					
Ap1	0- 5	22.7^{a} (0.1)	3.71	69.1^{a} (7.0)	16
Ap2	5-15	24.0^{b} (0.3)	3.81	37.1^{c} (3.3)	16
Ap3	15-25	24.5^{b} (0.4)	4.30	31.2^{c} (2.2)	18
Bs	25-40	28.1^{c} (1.0)	5.00	31.3^{c} (9.3)	18
BC^{b}	40-60	28.5	6.76	41.9	30
C^{b}	60-80	nd	5.95	nd	nd

[a] Aq-K was analysed on composite samples from the 5 plots
[b] The BC and C horizons were analysed as composite samples
nd=not determined

Altogether the total K based on partitioning of K amongst the K bearing minerals (Table 8) resulted in 100 ±10% of the directly measured Tot-K from the XRF analyses (Table 6), slightly overestimating total K in the Ap1-horizon and slightly underestimating it in the B-horizon, but nonetheless indicating a very good agreement between the two independent estimates.

Long-term budget calculations and changes in soil K pools

Mass balance calculations for the entire experimental period were used to estimate the total K off-take. The accumulated deficit for the 30-year period was similar for the K0 and K65 treatments, i.e. about 1150-1200 kg K ha^{-1}, which can be assumed to have been taken up from the soil pools within the rooting zone (Soil$_{K}$) (Table 9).

A change in Soil$_{K}$ can either be as exchangeable K or in the fixed or mineral bound K pool. The changes in exchangeable K (using Ac-K as an estimate) were calculated for the 30 year period by comparing the Ac-K (0-15 cm) before the treatments were applied with that measured in the soil samples taken 30-years later. The comparison showed that Ac-K decreased by about 50 kg K ha^{-1} during

Table 6 Soil K pools in the soil horizons, kg K ha^{-1}, in the K0 and K65 treatments 30 years after the start of the experiment. Total K (Tot-K), aqua regia extractable K (Aq-K) and acetic acid extractable K (Ac-K) were analysed on the < 2 mm fraction.

Treatment/ Horizon	Depth, cm	Tot-K, kg ha^{-1}	Aq-K^{a}, kg ha^{-1}	Ac-K, kg ha^{-1}
K0				
Ap1	0- 5	8 130	1 326	19
Ap2	5-15	15 535	2 508	21
Ap3	15-25	19 440	3 482	24
Bs	25-40	27 948	5 494	34
BC^{b}	40-60	40 470	9 599	59
C^{b}	60-80	nd	8 449	nd
Total in the rooting zone	0-40 cm	71 053	12 810	98
K65				
Ap1	0- 5	8 059	1 319	25
Ap2	5-15	15 600	2 475	24
Ap3	15-25	19 600	3 436	25
Bs	25-40	28 662	5 102	32
BC^{b}	40-60	40 470	9 599	59
C^{b}	60-80	nd	8 449	nd
Tot in rooting zone	0-40 cm	71 921	12 333	106

[a] Aq-K was analysed on composite samples from the 5 plots
[b] The BC and C horizons were analysed as composite samples for the field
nd=not determined

Table 7 Quantification of soil mineralogy (weight %), K-bearing and other minerals in the <2mm fraction (XRPD)

Horizon	Depth cm	K-bearing minerals^{a}					Other
		Kf	Mu	Illi	Bio	Hy-bio	minerals
Ap1	0- 5	10	8	1	1	4	63
Ap2	5-15	10	7	1	1	3	65
Ap3	15-25	10	8	1	1	4	65
Bs	25-40	10	6	1	1	7	65
BC	40-60	10	9	1	2	5	68
C	60-80	9	9	1	3	6	67

[a] Kf=K-feldspars, Mu=muscovite, Illi=illite, Bio=biotite, Hy-bio=hydrobiotite

Table 8 Partitioning of K between the different K bearing minerals, K-feldspar (Kf), muscovite (Mu), illite (Illi), biotite (Bio) and hydrobiotite (Hy-bio), given as kg K ha^{-1} in the mineral phases in the sampled soil horizons. Tot Min-K is the sum of K in these minerals

Horizon	Depth, cm	K - Kf	K - Mu	K - Illi	K - Bio	K - Hy-bio	Tot Min-K
Ap1	0- 5	5160	2750	160	220	650	8930
Ap2	5-15	9150	4920	310	440	990	15810
Ap3	15-25	11580	6370	330	340	1480	20100
Bs	25-40	14020	6620	690	800	3060	25180
BC	40-60	20870	11980	770	2220	3050	38890
C	60-80	18450	12330	710	3180	3610	38270
Tot in rooting zone	0-40 cm	39910	20660	1490	1800	6180	70020

Table 9 Accumulated K mass balances for the K0 and K65 treatments for the entire experimental period, kg K ha^{-1}

	K0	K65
Input	+448	+1969
Output	-1608	-3158
Balance (Deficit)	-1160	-1189
Change (Decrease) in Ac-K (0-15 cm)	+52	+31
Unaccounted for[a]	+1108	+1158

[a] Release of non-exchangeable K and/or uptake from subsurface horizons (>15 cm depth)

the first few years of the experiment (and then appeared to have stabilized there). This is a minor change in relation to the accumulated net off-take (deficit), leaving 1100-1150 kg K ha^{-1} unaccounted for (Table 9), that presumably has originated from fixed and mineral bound K sources and/or was taken up by roots in deeper soil horizons (below 15 cm). Since the Ac-K pool in the rooting zone (0-40 cm) was estimated at about 100 kg ha^{-1} by the end of the experimental period (Table 6), the main part of the K 'unaccounted' for can be assumed to have been released from the non-exchangeable and structural mineral K pool. This means that in total 1100 kg K ha^{-1} has been released from these fractions over a 30 year period which corresponds to about 35 kg K ha^{-1} yr^{-1}.

Discussion

While somewhat extreme, the zero (K0) and low (K65) fertiliser K treatment and exploitative nature associated with regular herbage cuts and removal means that considerable K net off-take occurred over the 30 year experimental period. It is readily apparent from both herbage yield and K compositional data that especially the K0 treatment K became the growth limiting nutrient element. The coarse soil texture (loamy sand) and granitic parent material also contributed to make this study relevant for large areas of (medium to lower productive) agricultural land. By combining detailed soil profile sampling including both chemical and mineralogical analyses with these accumulated negative K balances (net K off-take) an attempt has been made to quantify the underlying mechanisms controlling K cycling in this soil.

Potassium – the limiting nutrient for plant growth

Herbage K concentrations reached values as low as 0.5-0.7% in the K0 treatment (Fig. 1b), a value below that reported as the 'critical limit' for K in many previous field studies (Whitehead 2000). First indications of a yield difference between K65 and K0 treatments occurred at herbage concentrations of ~ 1%. However, the species composition is an important factor to consider when determining the critical K concentration and may explain some of the differences with published findings. The analysis of herbage taken from individual cuts showed low K concentrations (0.7%) all through the season in K0 whereas in K65 there was a decline in K% with cut 3 reaching 1% (Table 3). The similar low herbage K concentrations in K0 in all three cuts (Table 3) indicated that K probably was the growth limiting factor all through the season and thus 'testing' the systems limits in terms of K release capacity.

Øgaard et al. (2002) studied the effects of K-fertiliser application rates in grass herbage trials (dominated by timothy, *Phleum pratense* L., and meadow fescue, *Festuca pratensis* L.), and found that on sandy soils low in K there was a positive yield response on addition of K fertiliser the second and third year where grass K concentrations were 1.0-1.4%. Exhaustive cropping with perennial ryegrass (*Lolium perenne* L.) in a pot experiment, demonstrated that at concentrations of 0.6-0.8% K (Ghorayshi and Lotse 1986) growth essentially ceased. In long-term fertility trials (40 years) Andersson et al. (2007) found no yield reduction and maintained grass/clover herbage K concentration of ~2% in K nil plots on silty clay and clay soils. However, on sandy loam and loam soils herbage concentrations were generally less than 2% K, and, although it came down to 1% in one case, no effects on yield were recorded. The studied plots were fertilised with N but not P or K, and possibly P had become the limiting element prior to K in these systems, not 'pushing' the K delivering capacity as hard as in the experiment described herein.

Plant available soil K

Exchangeable and soil solution K have often been considered readily available for plants (e.g., Sparks 1987), while fixed and structural K are less available (e.g., Pal et al. 1999). The exchangeable K pool, usually extracted by ammonium acetate, ammonium lactate, ammonium nitrate, acetic acid or similar, as used in soil tests for fertiliser recommendations (e.g., Egnér et al. 1960; Thomas 1982; Rowell 1994; MISR/SAC 1985; MAFF, 1986), were replenished about 10 times during the 30 year experiment (Tables 6 and 9), suggesting a lack of sensitivity in this measurement to reflect actual plant availability of soil K. This indicated that substantial amounts of "non-exchangeable" K had been released during the experimental period and made available for plant uptake. In fact, several studies have shown that release of fixed or structural K can contribute significantly to plant supply (e.g., Sinclair 1979a; 1979b; Andrist-Rangel et al. 2007; Simonsson et al. 2007) and thus calling for a new approach to 'plant available K'. The demand for sustainable use of natural resources, including K fertiliser raw material (mined KCl and K_2SO_4) that has a rather limited distribution globally (regions such as Africa, Asia and Oceania have to rely on import) and rapidly increasing prices of agricultural inputs are also pertinent in this regard (e.g. Manning 2010).

In a K depleted soil the exchangeable K (i.e. Ac-K) concentration by the end of the growing season indicates a soil specific property to bind and release K; and whereas in certain soil types the release rate of K is slow and will restrict yields markedly in other parent materials it will meet all crop needs (McLean and Watson 1985). After some initial years, Ac-K in Grass I was on average 39 mg kg^{-1}, whereas in Grass II it was 28 mg kg^{-1} (Fig. 2). The lower Ac-K in the autumn in Grass II might be due to the fact that three cuts were taken while in Grass I the grass was cut only twice a year. This can be compared with the results of a pot experiment with intensive rye grass cropping to reach K exhaustion on soils from the same soil association (Sinclair 1979a) where the exchangeable K (average for two course textured granitic soils of the Countesswells Association) was 34 mg kg^{-1} when the soil was partly depleted (after 6-8 cuts, low yield level) and 26 mg kg^{-1} in the more depleted soil (after 9-12 cuts, growth virtually ceased). The similarity between the results from the field experiment and the pot trial indicates that the K release rate has been governed by the parent material of the soil and the plant-soil system. This includes a combination of soil mineralogy, particle size (or rather specific surface area), rooting depth and density, efficiency in K uptake, etc., all factors determining the soil solution K concentration and thus controlling the diffusion of K e.g. from interlayer positions of micas (e.g. Newman, 1969; Fanning et al 1989).

Annual K off-take and soil K pools

In this study, the accumulated total K net-deficit was about 1100 kg K ha^{-1}, i.e. on average 35 kg K ha^{-1} yr$^{-1,}$ and the question arises as to how this can be related to different K sources. The Tot-K soil concentrations were rather high, 23-28 g K kg^{-1}, as compared to 5-40 g K kg^{-1} recorded in a range of Scottish agricultural soils (Andrist-Rangel et al. 2010) and 0.4-30 g K kg^{-1} reported as a typical range in mineral soils globally (Sparks 1987). Thus the Tot-K pool in the rooting zone was very large (72 000 kg K ha^{-1}) indicating that the soil was very rich in mineral bound K. The chemically defined Aq-K pool (0-40 cm) was 12 000 kg ha^{-1}, which equated to 17% of the Tot-K. That can be compared to a study of Scottish grassland soils showing an average extractability of 13% (9-17%, n=3) for similar soils (Countesswells Association) (Andrist-Rangel et al. 2010).

However, the type of K bearing minerals influence the potential rate of release through mineral weathering and thus plant supply. Of the K bearing minerals that were identified in the soil, biotite is the one most prone to release K followed by hydrobiotite (e.g. Thompson and Ukrainczyk 2002). The estimated K pool in terms of these minerals showed that by the end of the 30 year period the rooting zone contained 8 000 kg K ha^{-1} in the form of biotite and hydrobiotite. Assuming that the C horizon is representative of the material the soil was derived from there was originally 13 600 kg ha^{-1} K in biotite and hydrobiotite (Table 8). Comparing that to the present situation, the difference is 5600 kg K, which can be seen in relation to the K off-take of 1100 kg during the last 30 years. A hypothetic calculation of continued intensive grass production, with no or low K fertiliser application and an annual net K off-take of 35 kg, would completely deplete the K present in trioctahedral micas in a bit more than two centuries. Taking the relative root distribution into account showing that most roots were in the top 25 cm the (84%, Table 1), where the K pool in biotite and hydrobiotite was 4100 kg K ha^{-1} (Table 8), and applying the release (net-off take) rate of 35 kg K ha^{-1} yr^{-1} the K-biotite and -hydrobiotite pool would last for another 120 or 140 years assuming 84 and 100% uptake from this soil layer.

Although these are very rough estimates, the findings can be related to laboratory studies of release mechanisms of interlayer K in micas. Newman (1969) found that micas release interlayer K by cation exchange and diffusion, a process that is governed by low solution concentration of K. The dioctahedral micas were found to be less reactive than trioctahedral micas and thus required a considerable (two orders of magnitude) lower solution concentration of K to release interlayer K. The study by Newman (1969) also showed that the release rate of K was largely independent of the proportion of mica K being exchanged. Applying this conceptually to the results of the present study, it seems most likely that the K delivering capacity in the experimental soil is regulated by grass uptake of K from the soil solution and hence the release rate of interlayer K in trioctahedral (biotite and hydrobiotite) micas, and that the release rate might remain at a similar level until most biotite and hydrobiotite is K depleted and thereafter change (decrease) drastically when dioctahedral micas (and K feldspars) become the main K source for plants.

Estimation of K release from soil resources

Simonsson et al. (2007) found that when receiving no K (or P, but N) for 40 years, a loamy sand soil released 8 ± 10 kg K ha^{-1} yr^{-1}, whereas four other soils (sandy loams to clays) had been releasing 40±8, 45±10, 51±12, and 65±7 kg K ha^{-1} yr^{-1} during the same period of time. This can be compared with the 35 kg K ha^{-1} yr^{-1} on average taken out from the loamy sand in this study. A simplified view has been that the soil K release and fixation capacity is mainly related to soil texture, particularly the fine textured material. However, that is not fully supported by this study, or other recent field studies (e.g., Andrist-Rangel et al. 2007; Murashkina et al. 2007), which have shown the importance of the mineralogical composition of coarser fractions, in particular the occurrence of biotite and hydrobiotite in the silt fraction. The main difference between the loamy sand in this study as compared to the one studied by Simonsson et al. (2007) was the mineralogy and in particular the presence of biotite and hydrobiotite, in total accounting for 4-8% of the minerals in the former but only 1-2% in the latter (Andrist-Rangel, 2008). Other differences were numbers of years with grass or grass/clover herbage in relation to cereal crops and the climate.

In order to predict the K weathering potential of different soils, soil mineralogy and other soil properties, cropping systems, management practices, climate etc have to be taken into account and a modelling approach would be needed. Some first attempts to apply the biogeochemical steady-state model PROFILE on some northern European agricultural soils were carried out by Holmquist et al (2003) who estimated K weathering rates of between 3 and 82 kg ha^{-1} yr^{-1}. A comparison between K release estimates from net off-take based on mass balance calculations (Table 9) and modelled weathering rates for the studied Countesswells soil showed, however, a large discrepancy between field based estimates and model predictions, 35 versus 5 (uncertainty range 2-16) kg K ha^{-1} yr^{-1} (Holmquist et al. 2003). This difference is most likely related to a combination of factors that include the small clay content and specific surface area of the soil, parameters that the PROFILE model is very sensitive to (e.g. Hodson et al. 1997). There is also an issue as to how the weathering of micas is represented within the model in terms of chemical reactions (Warfvinge and Sverdrup 1992; Sverdrup and Warfvinge 1993) because diffusion controlled exchange of interlayer K might be expected to be the dominant process in agricultural soils maintained at near neutral pH values (e.g. Fanning et al. 1989).

As mentioned earlier, there are orders of magnitude differences in critical K solution activity between di- and tri-octahedral micas (Newman, 1969; Fanning et al. 1989), i.e. in soils with tri-octahedral micas (such as biotite) they will become the main K source for plant supply in K depleted/low input systems. When interlayer K in biotite has been released and dioctahedral mica (and/or K feldspar) becomes the major K source the release rate will most probably decrease considerably since much lower solution concentrations of K are required for diffusion. This means that the release of K from soil resources observed in this and other long-term experiments will not be constant over time or related to the total K pool but very dependent on the types and amount of K bearing minerals, in particular the presence of tri-octahedral micas.

The long-term field data obtained from this study in combination with the quantitative mineralogical and geochemical characterisation of the soil and data from the literature (e.g. controlled laboratory experiments) have demonstrated the potential and need for further developing an approach linking mechanistic and quantitative assessment of plant K uptake and release from mineral sources in agricultural systems including predictions of K weathering rates. The increasing prices of agricultural inputs such as fertilisers and the increasing awareness of limited availability and uneven distribution of non-renewable resources (including soils) are reinforcing a better knowledge, use and management of site-specific resources for developing and maintaining sustainable production systems which requires cross-disciplinary research linking up basic and applied sciences within biogeochemistry and agricultural sciences.

Conclusions

This study has shown that K became the growth limiting nutrient element all through the growing season 'pushing' the K release capacity of the soil. The plant (perennial rye grass) K concentration was lower (0.6-0.7%) than reported in most previous field studies. The relation between the average annual K net-off take (35 kg ha^{-1}) and the quantified exchangeable K pool (~ 100 kg ha^{-1}), often assumed to represent 'plant available' K, illustrated that 'non-exchangeable' K had been continually released and made available for plant uptake. Hence, the perception of 'plant available K' needs to be reassessed taking the dynamics of the soil K resource(s) into account. The accumulated net K off-take (1 100 kg ha^{-1} during 30 year) was higher than previously reported from coarse texture soils derived from granitic parent material. The relatively high concentration of trioctahedral micas, i.e. biotite and hydrobiotite, was most probable the main K source. However, assuming a continued low input management system with similar net K off-take these easily weatherable minerals would be depleted of K within two centuries, something that needs to be considered in land-use and nutrient management.

The study illustrates the strength of combining long-term field experimental data with state of the art quantitative mineralogical methods in order to assess site-specific resources which can form a basis to evaluate the sustainability of different management practices. It shows how long-term field experimental data can be utilized to obtain quantitative measures on the potential K release in low input systems in different soil environments in order to better interpret K input/output field mass balances, predict the long-term sustainability of different farming practices, and suggest possible land-use and management options. Including an integrated modelling approach would be an important component to come further in research and implementation within this area. The increasing prices of agricultural inputs such as K fertilisers and the increasing awareness of limited availability of non-renewable resources are reinforcing a better knowledge and use of site-specific resources for developing and maintaining sustainable production systems.

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References

Adamo P, McHardy WJ, Edwards AC (1998) SEM observations in the back-scattered mode of the soil-root zone of *Brassica napus* (cv. Rafal) plants grown at a range of soil pH values. Geoderma 85: 357-370

Alfaro MA, Jarvis SC, Gregory PJ (2003) Potassium budgets in grassland systems as affected by nitrogen and drainage. Soil Use Manage 19: 89-95

Andersson S, Simonsson M, Mattsson L, Edwards AC, Öborn I (2007) Response of soil exchangeable and crop potassium concentrations to variable fertiliser and cropping regimes in long-term field experiments on different soil types. Soil Use Manage 23:10-19

Andrist-Rangel Y (2008) Quantifying mineral sources of potassium in agricultural soils. Doctoral Thesis No 2008: 53, Faculty of Natural Resources and Agricultural Sciences, Acta Universitatis Agriculturae Sueciae, Uppsala

Andrist-Rangel Y, Simonsson M, Andersson A, Öborn I, Hillier S (2006) Mineralogical budgeting of potassium in soil: A basis for understanding standard measures of reserve potassium. J Plant Nutr Soil Sci 169: 605-615

Andrist-Rangel Y, Edwards AC, Hillier S, Öborn I (2007) Long-term K dynamics in organic and conventional mixed cropping systems as related to management and soil properties. Agric Ecosyst Environ 122: 413-426

Andrist-Rangel Y, Hillier S, Öborn I, Lilly A, Towers W, Edwards AC, Paterson E (2010) Assessing potassium reserves in northern temperate grassland soils: A perspective based on quantitative mineralogical analysis and aqua-regia extractable potassium. Geoderma (accepted)

Askegaard M, Eriksen J (2002) Exchangeable potassium in soil as indicator of potassium status in an organic crop rotation on loamy sand. Soil Use Manage 18: 84-90

Askegaard M, Eriksen J, Olesen JE (2003) Exchangeable potassium and potassium balances in organic crop rotations on a coarse sand. Soil Use Manage 19: 96-103

Askegaard M, Eriksen J, Johnston AE (2004) Sustainable management of potassium. In: Schjønning P, Elmholt S, Christensen BT (ed) Managing soil quality - Challenges in modern agriculture, CAB International, Wallingford, 85-102

Askegaard M, Eriksen J (2008) Residual effect and leaching of N and K in cropping systems with clover and ryegrass catch crops on a coarse sand. Agric Ecosyst Environ 123: 99-108

Barré P, Velde B, Catel N, Abbadie L (2007) Soil-plant potassium transfer; impact of plant activity on clay minerals as seen from X-ray diffraction. Plant Soil 292: 137-146

Barré P, Velde B, Fontaine C, Catel N, Abbadie L (2008) Which 2:1 clay minerals are involved in the soil potassium reservoir? Insights from potassium addition or removal experiments on three temperate grassland soil clay assemblages. Geoderma 146: 216-223

Barré P, Berger G, Velde B (2009) How element translocation by plants may stabilize illitic clays in the surface of temperate soils. Geoderma 151: 22-30

Bedrossian S, Singh B (2004) Potassium adsorption characteristics and potassium forms in some New South Wales soils in relation to early senescence in cotton. Aust J Soil Res 42: 747-753

Bell MJ, Moody PW, Harch GR, Compton B, Want PS (2009) Fate of potassium fertiliser applied to clay soils under rainfed grain cropping in south-east Queensland, Australia. Aust J Soil Res 47: 60-73

Bengtsson H, Öborn I, Jonsson S, Nilsson I, Andersson A (2003) Field balances of some mineral nutrients and trace elements in organic and conventional dairy farming – a case study at Öjebyn, Sweden. Eur J Agron 20: 101-116

Berry PM, Stockdale EA, Sylvester-Bradley R, Philipps L, Smith KA, Lord EI, Watson CA, Fortune S (2003) N, P and K budgets for crop rotations on nine organic farms in the UK. Soil Use Manage 19: 112-126

Brady NC, Weil RR (1996) The Nature and properties of soils, 11th Ed, Prentice-Hall, Upper Saddle River, New Jersey

Broad HJ, Hough MN (1993) The growing and grazing season in the United Kingdom. Grass Forage Sci 48: 26-37

Edwards AC, Mackie-Dawson LA, Millard P, Shepherd H, Reid ME, Webster L, Pratt S, Stott C (1987) Quantify the availability of soil and fertiliser phosphorous to crops by chemical methods and field trials and assess interactions with acidity. In: Macaulay Land Use Research Institute, Report of Work in Progress 1987, Craigiebuckler, Aberdeen, pp 171-173

Egnér H, Riehm H, Domingo WR (1960) Untersuchungen über die Chemische Bodenanalyse als Grundlage für die Beurteilung des Nährstoffzustandes der Böden. Ann Roy Agr Coll Sweden 26: 199–215

Fanning DS, Keramidas VZ, El-Desoky MA (1989) Micas. In: Dixon JB, Weed SB Minerals in Soil Environments, 2nd Ed. SSSA Book Series No 1, Madison, WI, pp 551-634

Fortune S, Robinson JS, Watson CA, Philipps L, Conway JS, Stockdale EA (2005) Response of organically managed grassland to available phosphorus and potassium, in the soil and supplementary fertilization: field trials using grass-clover leys cut for silage. Soil Use Manage 21: 370-376

Foy RH, Bailey JS, Lennox SD (2002) Mineral balances for the use of phosphorus and other nutrients by agriculture in Northern Ireland from 1925 to 2000 – methodology, trends and impacts of losses to water. Irish J Agr Food Res 41: 247–263

Ghorayshi M, Lotse E (1986) Quantity Intensity Relationships of Potassium in 3 Swedish Soils. Swed J Agr Res 16: 57-65

Glentworth RS, Muir JW (1963) The soils around Aberdeen, Inverurie, and Fraserburgh. Soil Survey of Scotland Memoirs. The Macaulay Institute for Soil Research, Aberdeen

Goulding KTW, Loveland PJ (1986) The classification and mapping of potassium reserves in soils of England and Wales. J Soil Sci 37: 555-565

Gustafson GM, Salomon E, Jonsson S (2007) Barn balance calculations of Ca, Cu, K, Mg, Mn, N, P, S and Zn in a conventional and organic dairy farm in Sweden. Agric Ecosyst Environ 119: 160-170

Haak E (1981) Nutrient uptake from subsoil by cereals. In: Agricultural yield potentials in continental climates. Proceedings of the 16th Colloquium of the International Potash Institute, Basel

Hanson AA (1990) Practical handbook of agricultural science, CRC Press, Boca Raton, Florida

Heming SD (2004) Potassium balances for arable soils in southern England 1986-1999. Soil Use Manage 20: 410-417

Hillier S (1999) Use of an air brush to spray dry samples for X-ray powder diffraction. Clay Miner 34: 127-135

Hillier S (2003) Quantitative analysis of clay and other minerals in sandstones by X-ray powder diffraction (XRPD). Int Assoc Sedimentol Spec Publ 34: 207–245

Hinsinger P, Jaillard B (1993) Root-induced release of interlayer potassium and vermiculitization of phlogopite as related to potassium depletion in the rhizosphere of ryegrass. J Soil Sci 44: 525-534

Hodson ME, Langan SJ, Wilson MJ (1997) A critical evaluation of the use of the PROFILE model in calculating mineral weathering rates. Water Air Soil Poll 98: 79-104

Holmqvist J, Falk Øgaard A, Öborn I, Edwards AC, Mattsson L, Sverdrup H (2003) Application of the PROFILE model to estimate potassium release from mineral weathering in Northern European agricultural soils. Eur J Agron 20: 149-163

Huang PM (1989) Feldspars, Olivines, Pyroxenes, and Amphiboles In: Dixon JB, Weed SB Minerals in Soil Environments, 2nd Ed. SSSA Book Series No 1, Madison, WI, pp 975-1050

Kayser M, Isselstein J (2005) Potassium cycling and losses in grassland systems: A review. Grass Forage Sci 60:213-224

Kuhlmann H (1990) Importance of the subsoil for the K-nutrition of crops. Plant Soil 127: 129-136

MAFF (1986) The analysis of agricultural materials, 3rd Ed. Reference Book 427. Defra, Information Resource Centre, London

Manning DAC (2010) Mineral sources of potassium for plant nutrition. A review. Agron Sustain Dev 30: 281-294

Mclean EO, Watson ME (1985) Soil measurements of plant-available potassium. In: Munson (ed) Potassium in agriculture, ASA-CSSA-SSSA Madison, WI, 277-308

McGrath SP (1987) Computerized quality control, statistics and regional mapping of the concentrations of trace and major elements in the soils of England and Wales. Soil Use Manage 3: 31–38

McGrath SP, Cunliffe CH (1985) A simplified method for the extraction of the metals Fe, Zn, Cu, Ni, Cd, Pb, Cr, Co, and Mn from soils and sewage sludges. J Sci Food Agric 36: 794–798

MISR/SAC (1985) Advisory soil analysis and interpretation. The Macaulay Institute for Soil Research and Scottish Agricultural Colleges Bulletin 1: 1-13

Murashkina MA, Southard RJ, Pettygrove GS (2007) Silt and fine sand fractions dominate K fixation in soils derived from granitic alluvium of the San Joaquin Valley, California. Geoderma 141: 283-293

Newman ACD (1969) Cation exchange properties of micas. I. The relation between mica composition and potassium exchange in solutions of different pH. J Soil Sci 20: 357-373

Norrish K, Hutton JT (1969) An accurate X-ray spectrographic method for the analysis of a wide range of geological samples. Geochim Cosmochim Acta 33: 431-453

Öborn I, Andrist-Rangel Y, Askegaard M, Grant CA, Watson CA, Edwards AC (2005a) Critical aspects of potassium management in agricultural production systems. Soil Use Manage 21: 102-112

Öborn I, Modin-Edman A-K, Bengtsson H, Gustafson GM, Salomon E, Nilsson SI, Holmqvist J, Jonsson S, Sverdrup H (2005b) A systems approach to assess farm-scale nutrient and trace element dynamics: A case study at the Öjebyn dairy farm. Ambio 34: 301-310

Øgaard AF, Krogstad T, Lunnan T (2002) Ability of some Norwegian soils to supply grass with potassium (K) – soil analyses as predictors of K supply from soil. Soil Use Manage 18: 412-420

Omotoso O, Mccarty DK, Hillier S, Kleeberg R (2006) Some successful approaches to quantitative mineral analysis as revealed by the 3rd Reynolds Cup contest. Clay Clay Miner 54: 748-760

Pal Y, Wong MTF, Gilkes RJ (1999) The forms of potassium and potassium adsorption in some virgin soils from south-western Australia. Aust J Soil Res 37: 695-709

Reid JM, MacLeod DA, Cresser MS (1981) Factors affecting the chemistry of precipitation and river water in an upland catchment. J Hydrol 50: 129-145

Robert M (1992) K-fluxes in soils in relation to parent material and pedogenesis in tropical, temperate and arid climates. Proceedings of the 23rd Colloquium of the International Potash Institute, Basel, pp 25-44

Rowell DL (1994) Soil science methods and applications. Longman, Singapore, pp 66-67

Simonsson M, Andersson S, Andrist-Rangel Y, Hillier S, Mattsson L, Öborn I (2007) Potassium release and fixation as a function of fertilizer application rate and soil parent material. Geoderma 140: 188-198

Sinclair AH (1979a) Availability of potassium to ryegrass from Scottish Soils I. Effects of intensive cropping on potassium parameters. J Soil Sci 30: 757-773

Sinclair AH (1979b) Availability of potassium to ryegrass from Scottish Soils II. Uptake of initially non-exchangeable potassium. J Soil Sci 30: 775-783

Singh B, Goulding KWT (1997) Changes with time in the potassium content and phyllosilicates in the soil of the Broadbalk continous whear experiment at Rothamsted. Eur J Soil Sci 48: 651-659

Skinner RJ, Todd AD (1998) Twenty-five years of monitoring pH and nutrient status of soils in England and Wales. Soil Use Manage 14: 162-169

Smaling EMA, Oenema O, Fresco LO (eds) (1999) Nutrient disequilibria in agroecosystems. Concepts and case studies. CABI, London

Sparks DL (1987) Potassium dynamics in soils. In: Stewart BA (ed) Advances in Soil Science. Springer-Verlag, New York, pp 1-63

Sparks DL, Huang PM (1985) Physical chemistry of soil potassium. In: Munson (ed) Potassium in agriculture, ASA-CSSA-SSSA Madison, WI, 201-276

Sverdrup H, Warfvinge P (1993) Calculating field weathering rates using a mechanistic geochemical model PROFILE. Appl Geochem 8: 273-283

Systat (1998) SYSTAT for Windows: Statistics Version 8.0, Evanston IL Systat

Inc 1086 pp

Thomas GW (1982) Exchangeable cations. In: Page AL, Miller RH, Keeney DR (ed) Methods of soil analysis, Part 2, Agronomy Monograph no 9 2nd Ed, pp 159-165

Thompson ML, Ukrainczyk L (2002) Micas. In: Dixon JB, Schulze DG (ed) Soil mineralogy with environmental applications, SSSA Book Series No 7, Madison, WI, pp 431-466

Warfvinge P, Sverdrup H (1992) Calculating critical loads of acid deposition with PROFILE – a steady state soil chemical model. Water Air Soil Poll 63: 119-143

Watson CA, Bengtsson H, Ebbesvik M, Løes A-K, Myrbeck A, Salomon E, Schroeder J, Stockdale EA (2002) A review of farm-scale nutrient budgets for organic farms as a tool for management of soil fertility. Soil Use Manage 18: 264-273

Whitehead DC (2000) Nutrient elements in grassland. Soil-plant-animal relationships. CAB International Wallingford UK

Wilson MJ (1992) K-Bearing minerals and their K-release rates in different climates. Proceedings of the 23rd Colloquium of the International Potash Institute, Basel, pp 44-57

Wilson MJ (2004) Weathering of the primary rock-forming minerals: Processes, products and rates. Clay Miner 39: 233-266.

Witter E, Johansson G (2001) Potassium uptake from the subsoil by green manure crops. Biol Agric Hortic 19: 127-141

Wulff F, Schulz V, Jungk A, Claassen N (1998) Potassium fertilization on sandy soils in relation to soil test, crop yield and K-leaching. Z Pflanz Bodenkunde 161: 591-599

State-wise approach to crop nutrient balances in India

T Satyanarayana • RK Tewatia

Abstract India registered an ever recorded food grain production of 230 mt with a consumption of 23 mt of NPK's during 2007-08 and it was estimated that about 45 mt of nutrients are needed to produce 300 mt of food grains by 2025 to sustain the requirement of growing population. Present intensive production systems in India characterized by heavy removal and inadequate replenishment of nutrients resulted in multiple nutrient deficiencies and depletion of soil nutrient reserves. For sustaining the crop productivity and to restore the soil fertility, there is a need to arrest depletion of soil nutrient reserves for which understanding of crop nutrient balances is important. An attempt was made to generate information on nutrient balances in some of the agriculturally important states considering the present scenario of nutrient additions and crop removals at current levels of crop production. N, P driven agriculture with neglect of K has shown an alarming situation of negative K balance in almost all the states with reported deficiencies of secondary and micronutrients. The present paper review the status of nutrient balances in different states and suggests approaches for balancing the existing nutrient gaps.

Keywords Apparent nutrient balances • crop removal • nutrient additions • soil health • yield sustainability

Introduction

Crop management in India during the past four decades has been driven by increased use of external inputs. Fertilizer nutrients have played a major role in improving crop productivity. During the period 1969-2008, food grain production more than doubled from about 98 mt to a record 230 mt in 2007-08, while fertilizer nutrient use increased by nearly 12 times from 1.95 mt to more than 23 mt in 2007-08 (Rao 2009). Notwithstanding these impressive developments, food grain

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demand is estimated to increase to about 300 mt yr^{-1} by 2025 for which the country would require 45 mt of nutrients (ICAR 2008). With almost no opportunity to increase the area under cultivation over 142 m ha, much of the desired increase in food grain production has to be attained through yield enhancement in per unit area productivity. To sustain production demands, the productivity of major crops has to increase annually by 3.0 to 7.5 percent (NAAS 2006). Much of this has to be met by increasing genetic potential and improved production efficiency of the resources and inputs like water and nutrients. In addition, the growing concern about poor soil health and declining factor productivity or nutrient use efficiency has raised concern on the productive capacity of agricultural systems in India. Major factors contributing to the low and declining crop responses to fertilizer nutrients are (a) continuous nutrient mining due to imbalanced nutrient use, which is leading to depletion of some of the major, secondary, and micro nutrients like P, K, S, Zn, Mn, Fe and B, and (b) mismanagement of irrigation systems leading to serious soil quality degradation. Furthermore, such low efficiency of resources and fertilizer inputs has impacted the production costs with serious environmental consequences.

Intensive agriculture is continuously being practiced in most of the states of India and therefore, the problems of soil fertility exhaustion and nutrient imbalances are bound to occur. The ill effects of exhaustive cropping systems are reflected on production of succeeding crops. In order to maintain the optimum level of production, it is necessary to know the nutrient requirement of crops, fertility status of the soil and the amount of nutrient removal from the soil by crops. During 1999-2000, the crop removal of nutrients is estimated to be about 28 mt while the fertilizer consumption was only 18 mt with an annual nutrient gap of 10 mt. Although a part of this nutrient gap is expected to be bridged from non-chemical sources like organic manures and biological processes, still there is a distinct gap in nutrient removal and supply leading to nutrient mining from the native soil posing a serious threat to long term sustainability of crop production (Hegde and Sudhakarbabu 2001). Furthermore, the country like India can hope to achieve and sustain the desired level of agricultural production in the long run only if we can bridge the gap between nutrient removal and addition. Therefore, understanding the present status of plant nutrient use and removal and the resultant nutrient balances in different states of the country with varied agro climatic conditions would enable us for undertaking the corrective measures to bridge the nutrient gap and help to maintain soil health and ensure the food and nutritional security. Information on nutrient balances would also help in developing an understanding about the annual loss of nutrients from the soil and to devise nutrient management strategies for rational use of soil resource in sustainable manner. It also gives insights into the level of fertilizer use efficiency and the extent to which externally added nutrients have been absorbed by the crop and utilized for yield production. It can also forewarn about nutrient deficiencies, which may aggravate in the coming years and need attention.

In India, state wise approaches to crop nutrient balances have been developed way back in 2001 considering the nutrient additions and removal data either from 1998-99 or 1999-2000. Since then, the information on nutrient balances has not been updated. Furthermore, for making future estimations, information on current nutrient balances is highly essential. Therefore an attempt has been made in this paper to generate fresh information on nutrient balances in major agriculturally important states of India considering the recent statistics of nutrient additions and removals as available from FAI (2008). Nutrient balance calculations in most of the cases do not give real picture as they consider nutrient removal by crops and addition through fertilizers neglecting contribution from sources other than fertilizers such as organic manures, crop residues and stubbles, irrigation water etc. However, in this paper, the authors have tried to overcome that limitation by considering nutrient additions through organic sources wherever possible from the information available in the published literature. While calculating nutrient removal by crops at the present production levels, emphasis has been made to consider removal of nutrients by fruits and vegetables in all the states; tea, coffee, jute, rubber and other plantation crops in states wherever applicable and the total production values have been multiplied with the nutrient uptake per tonne of produce and arrived at removal figures. During the discussions on nutrient balances in individual states, efforts have been made to compare the current scenarios with that of either 1998-99 or 1999-2000, the reason being the last nutrient balance studies were generated from the statistics of those years. Efficiency factors were involved for calculating net nutrient balances.

Nutrient balance scenario in major states of eastern India

Assam

Assam has 4 m ha of gross cropped area of which 14.5 percent is irrigated. Major portion of the soils of the state are Inceptisols (49.3 percent), followed by Entisols (32.3 percent), Alfisols (12.3 percent) and Ultisols (6.1 percent). Amongst several soil related constraints, high soil acidity especially in the uplands and transitional medium lands limits nutrient availability to the crops. The principal crops grown are rice, jute, potato, pulses, oilseeds, vegetables, sugarcane, fruits, tea etc and the cropping intensity of the state is around 145 percent. The share of area under food grains to gross cropped area is 71 percent. A variety of cropping systems are in practice in the state. The current fertilizer use in the state is 57.3 kg ha^{-1} consisting of 27.7, 14.6 and 15.0 kg ha^{-1} N, P_2O_5 and K_2O respectively, the $N:P_2O_5:K_2O$ use ratio being 1.8:0.9:1.0. The consumption of total fertilizer nutrients ($N + P_2O_5 + K_2O$) during 2007-08 was 214 thousand ton.

Nutrient balance scenario (Table 1) for the state of Assam shows that the crop removal being higher than that added, all the three NPK nutrients have a negative balance. Nutrient mining is found to be to the tune of 0.113, 0.011 and 0.199 mt of N, P_2O_5 and K_2O, respectively. If the similar trend of mining of nutrient reserves is allowed to continue without replenishment, worsen situations would lead to deterioration of soil health and decline in crop productivity. The soils of Assam being constrained with soil acidity, high phosphorus fixation, nutrient losses from soil along with socio-economic problems, the state needs special attention on adequate application of plant nutrients in order to achieve targeted crop production. Integrated nutrient management, organic recycling and supplementary nutrient addition are the keys to uphold productivity at high and sustained level.

Table 1 Nutrient additions, removal by crops and apparent balance in major states of Eastern India

State	Nutrients (000 t)			Mining Index (R/A)
	Additions (A*)	Removal (R*)	Balance	
Assam				
N	103.4	216.1	-112.8	2.1
P_2O_5	54.6	65.1	-10.5	1.2
K_2O	56.0	255.8	-199.8	4.6
NPK Total	213.9	537.1	-323.1	7.9
Bihar				
N	929.6	452.8	476.8	0.5
P_2O_5	191.6	203.2	-11.6	1.1
K_2O	84.4	646.4	-561.9	7.7
NPK Total	1205.6	1302.4	-96.8	9.2
Jharkhand				
N	89.4	122.5	-33.1	1.4
P_2O_5	45.8	59.5	-13.6	1.3
K_2O	9.8	169.6	-159.9	17.4
NPK Total	145.0	351.6	-206.6	20.0
Orissa				
N	272.1	264.9	7.2	1.0
P_2O_5	116.8	135.3	-18.5	1.2
K_2O	63.0	383.6	-320.6	6.1
NPK Total	451.9	783.8	-331.9	8.2
West Bengal				
N	684.5	676.7	7.8	1.0
P_2O_5	385.8	319.3	66.5	0.8
K_2O	304.4	972.8	-668.4	3.2
NPK Total	1374.7	1968.8	-594.1	5.0

A* - Nutrient additions only throw fertilizers being considered.
R* - Nutrient removal calculated as per FAI statistics.

Bihar

Agriculture in Bihar is the only backbone to the overall development of state. It has total geographical area of 9.37 m ha. The net cropped area stands at 5.7 m ha, of which 61.1 percent is irrigated. About 89 percent of the total cropped area of the state is under food grains and the current cropping intensity is 139.4 percent. The principal crops grown are rice, wheat, maize, pulses, oilseeds, vegetables, and sugarcane along with large acreage under fruits. The state is divided into four agro-climatic regions. Three major soil groups are recognized as foothill soils in the narrow strips of northern boundary, sedentary foot hill and forest soils in the southern boundary and remaining soils are dominantly of alluvial origin in the Indo-Gangetic plains. The current fertilizer use in the state is 162.8 kg ha^{-1} consisting of 125.5, 25.9 and 11.4 kg ha^{-1} N, P_2O_5 and K_2O respectively, the $N:P_2O_5:K_2O$ use ratio being 9.9:2.2:1.0. While most of the nitrogen, phosphorus and potassium are applied through urea, DAP (46 percent P_2O_5) and MOP (60 percent K_2O) respectively, a healthy share of complex fertilizers also contributes to the total NPK consumption in the state.

The total NPK removal by selected crops appears to be 1.30 mt as against the fertilizer nutrient addition of 1.21 mt. Thus, a net NPK depletion of 0.09 mt was recorded for the whole state (Table 1). The balance sheet indicates that the maximum removal was recorded with K followed by N and P. Potassium balance in the state is negative and this is very much expected under the situations when the potash removals by crops is much larger than its addition through fertilizers and other sources. The nutrient use pattern in Bihar is confined to N and P and the K fertilization is by and large neglected in most of the cases. Due to intensive cultivation, sulphur and micronutrients like Zn and B are also getting severely depleted from the soil. There is a need to exploit the prevailing practices of manuring and residue recycling, which are not satisfactory at the present level of cultivation. Integrated plant nutrient supply system seems to have a long way to go for maintaining soil health and sustaining yield in the state.

Jharkhand

Jharkhand has an area of 7.95 m ha and a population of 21.8 million. The state has about 2.2 m ha of net sown area, of which only 9 percent is irrigated. The red and lateritic soils forms the major group of soils encountered in the state and are generally poor in fertility, coarse textured, with low water and nutrient retention capacity. Farmers in the state generally grow direct seeded rice/finger millet or pulses in uplands and transplanted rice in low lands. Maize, rice, groundnut and oilseed crops cover medium lands. The productivity levels of these crops are very low owing to low nutrient inputs and poor inherent soil fertility of the region. The intensity of nutrient ($N + P_2O_5 + K_2O$) use through fertilizers in Jharkhand 68.5 kg ha^{-1} consisting of 42.3 kg N, 21.7 kg P_2O_5 and 4.6 kg K_2O with $N:P_2O_5:K_2O$ use ratio of 9.2:4.7:1.

Total removal of plant nutrients is around 0.352 mt out of which N, P_2O_5 and K_2O accounts for 0.123, 0.06 and 0.17 mt, respectively (Table 1). The total nutrient addition is only 0.145 mt with N, P_2O_5 and K_2O added at 0.089, 0.046 and 0.009 mt, respectively. Thus, there is a negative balance of 0.21 mt of NPK nutrients at the present levels of crop production in the state. This is really alarming and with the projected increase in population and associated food grain requirements for Jharkhand, the depletion in plant nutrients is likely to be alarming and requires serious consideration.

Orissa

The state of Orissa is known for mono-cropping of rice with other crops like pulses and oilseeds grown on residual moisture after rice. The state has 8.9 m ha of gross cropped area with cropping intensity of 157 percent. Major soils of the state are deltaic coastal soils, coastal saline soils, red and laterite soils, black soils and brown forest soils. The share of area under food grains to gross cropped area is 76 percent. The crop yields as well as crop removal of nutrients from the soil were very low and the natural processes of nutrient cycling, biological nitrogen fixation, addition of crop residues and FYM possibly sustained the nutrient balance of soil. The intensity of nutrients ($N + P_2O_5 + K_2O$) use through fertilizers in Orissa is very low at 51.8 kg ha^{-1} consisting of 31.2, 13.4 and 7.2 kg ha^{-1} N, P_2O_5 and K_2O, respectively with $N:P_2O_5:K_2O$ use ratio of 4.3:2.2:1. Though the share of Orissa to all India gross cropped area is 5.3 percent but its share to all India consumption of NPK is only 2 percent . The share of potash to total NPK consumption is 13.9 percent .

The state as a whole had a negative nutrient balance of 332 thousand tonnes of NPK nutrients. The nutrient balance with respect to N was found to be positive by 7.2 thousand tonnes where as phosphorus was negatively balanced at 18.5 thousand ton. . The total K removal by the crops at current level of productivity is 384 thousand ton against total addition of 63 thousand ton resulting in a severe negative K balance of 320 thousand ton. The current fertilizer use in Orissa is extremely low and has resulted in lower yield levels of most of the crops. Total nutrients added as fertilizers accounts for 58 percent of crop removal and fertilizer K added is about 16 percent of K removed by the crops. Unless fertilizer consumption is substantially increased, apart from perpetuating lower yields, there is an immediate danger of a steep decline of existing crop yields.

West Bengal

West Bengal is one of the agriculturally most important states of Eastern India having 9.6 m ha of gross cropped area of which 35 percent is irrigated. Major soils of the state are alluvial, red and laterites, coastal saline soils and hill and *terai* soils. The principal crops grown are rice, potato, pulses, oilseeds, vegetables, sugarcane, fruits, tea *etc*. The share of area under food grains to gross cropped area is 71 percent. A variety of cropping systems are in practice in the state. The current fertilizer use in the state is 144.2 kg ha^{-1} consisting of 71.8, 40.5 and 31.9 kg ha^{-1} N, P_2O_5 and K_2O, respectively, the $N:P_2O_5:K_2O$ use ratio being 2.4:1.2:1.0. Total fertilizer nutrient consumption in the state grew by 7.2 percent, from 1.283 mt during 1999-2000 to 1.375 mt during 2007-08. The consumption of N, P_2O_5 and K_2O at 0.697, 0.417 and 0.312 M t during 2007-08, recorded increase of 4.9, 7.8 and 14.7 percent, respectively, over 1999-2000.

The total removal of nitrogen during 2007-08 was 0.678 mt, however, the addition through fertilizers was 0.685 mt (Table 1). Therefore, the N balance in the state seems to be positive (0.008 mt) at present level of crop production. Phosphorus was positively balanced at 0.067 mt, however, the potassium balance was extremely negative. The total potassium removal by major crops at current level of productivity is 0.973 mt against total addition of 0.304 mt through fertilizers showing a negative balance of 0.668 mt. The total negative balance of NPK in the state is amounting to 0.594 mt.

Nutrient balance scenario in major states of northern India

Haryana

Haryana is an agriculturally important state of Northern India having 6 m ha of gross cropped area of which 81 percent is irrigated with cropping intensity of 170 percent. Major soils of the state are alluvial and saline - sodic with problems of salty waters in some parts. The principal crops grown are rice, wheat, pearl millet, cotton, sugarcane, mustard, chickpea, and potato. The share of area under food grains to gross cropped area is 71 percent. A five-fold increase in food grain production during the last 35 years combined with inadequate and unbalanced nutrient supply has led to a large degree of soil nutrient 'mining' of all the essential plant nutrients. Farmers in Haryana apply generalized quantities of N, P and Zn and as a consequence, deficiencies of K and other nutrients are spreading in space and time. The intensity of nutrients ($N + P_2O_5 + K_2O$) use through fertilizers in

Haryana is 187.6 kg ha^{-1} consisting of 144.4 kg N, 39.6 kg P_2O_5 and 3.6 kg K_2O with N: P_2O_5:K_2O use ratio of 59.7:18.6:1. Though the share of Haryana to all India gross cropped area is 3.2 percent but its share to all India consumption of NPK is 6 percent. The share of potash to total NPK consumption is only 1.93 percent.

The nutrient mining scenario in Haryana reveals that there was a gap of 0.78 mt between removal and additions of NPK nutrients through mineral fertilizers and other organic sources in the year 2007-08 (Table 2). Except for N showing a positive balance of 0.031 mt, both P and K balances were found to be negative. The N gap in the state has been improved from -22.5 thousand tonnes in 1999-2000 to +30.8 thousand tonnes which was mainly due to increase in fertilizer consumption from 109.13 kg ha^{-1} in 1999-2000 to 187.6 kg ha^{-1} in 2007-08. There is a negative balance of about 155 and 652 thousand tonnes of P and K in the state, which indicate that the depletion of both P and K would continue to increase in future, as a result more and more areas will come under the deficiency of these nutrients. Vinod Kumar et al. (2001) also reported a negative balance of S, Fe, Mn and Cu in the state though the Zn balance was positive due to application of Zn in rice and wheat crops. It is possible to narrow the gap between removal and additions through continuous recycling of nutrients and through balanced fertilizer use and encouraging combined use of fertilizers with organic manures, crop residues, green manuring and biofertilisers.

Table 2 Nutrient additions, removal by crops and apparent balance in major states of Northern India

State	Nutrients (000 t)			Mining Index (R/A)
	Additions (A)	Removal (R)	Balance	
Uttar Pradesh (a*)				
N	3180.7	1488.3	1692.4	0.5
P_2O_5	1023.6	591.8	431.8	0.6
K_2O	863.1	1842.1	-979.0	2.1
NPK Total	5067.4	3922.2	1145.2	3.2
Punjab (b*)				
N	1315.5	750.2	565.2	0.6
P_2O_5	343.9	446.3	-102.4	1.3
K_2O	38.4	1022.8	-984.5	26.7
NPK Total	1697.8	2219.3	-521.6	28.5
Haryana (c*)				
N	520.6	489.8	30.8	0.9
P_2O_5	65.1	220.3	-155.2	3.4
K_2O	16.6	669.1	-652.5	40.4
NPK Total	602.3	1379.2	-776.9	44.7

a* Inputs through fertilizers, irrigation water, crop residues and FYM considered
b* Inputs through fertilizer additions, contribution from other sources considered negligible
c* Additions through fertilizers, 1/3rd contribution of nutrients from cow dung and efficiency factors of 0.55, 0.25 and 0.66 were considered for NPK

Punjab

Punjab having 8.2 m ha of gross cropped area is one of the most important states of Northern India. In Punjab, 95 percent of the gross cropped area is irrigated with cropping intensity of 194 percent. Major soils of the state are alluvial in nature. The principal crops grown are rice, wheat, maize, cotton, sugarcane, mustard, chickpea, and potato. The share of area under food grains to gross cropped area is 77 percent. The total nutrient consumption in the state increased by 23.5 percent, from 1.38 mt during 1998-99 to 1.69 mt during 2007-08. The intensity of nutrients (N + P_2O_5 + K_2O) use in Punjab is 210 kg ha^{-1} consisting of 162.7 kg N, 42.5 kg P_2O_5 and 4.7 kg K_2O with N:P_2O_5:K_2O use ratio of 34.3:9.0:1 which evidently is highly unbalanced. Apparently, the share of potash in total NPK use in the State is only 2.3 percent, which is negligible.

Nutrient addition to crops is mainly through mineral fertilizers and the contribution of organic sources is marginal in the state. It is evident from Table 2 that the N balance in the state is positive at 565 thousand tonnes. However, with the current additions of 344 thousand tonnes of P_2O_5 as against 446 thousand tonnes of crop removal, the P balance in the state is negative by 102 thousand tonnes. The use of K in Punjab is almost negligible, whereas its removal is 36 and 129 percent greater than that of N and P. The total K removal by the crops at current level of productivity is 1.022 mt against total addition of 0.038 mt with the negative K balance of 0.985 mt. (Brar 2004) reported that total K loss from Punjab soils increased from 159 thousand tonnes in 1960-61 to 678 thousand tonnes by 2002-03. This wide gap in potash removal and addition has impoverished soil's potash reserves and thus the magnitude and extent of its deficiency and crop responses to its application are on increase in both time and space. Sulphur deficiency is predominantly seen in the state, limiting the yields of oilseeds, pulses and cereals. Current status of S balance is negative with mining of about 80 thousand tonnes annually in the state (Aulakh and Bahl 2001). Amount of Zn added was several times higher than its removal and as a result substantial amount of Zn was left in the balance owing to its poor utilization. There is a need to implement the 4 R's strategy of nutrient management focusing right quantity of nutrients through right source at right time by right methods of application, which would help in bridging the nutrient gaps in the state.

Uttar Pradesh

Uttar Pradesh is one of the agriculturally important states of Northern India with

17.6 m ha of gross cropped area, of which 72 percent is irrigated with cropping intensity of 152 percent. Major soils of the state are alluvial and saline – sodic (with some problems of salty waters) in Gangetic plains and residual soils in Bundel Khand . The principal crops grown are rice, wheat, maize, pearl millet, sorghum, mustard, pigeon pea, chickpea, pea, lentil, potato, sugarcane, vegetables and fruits The area under food grains is 78 percent of net cropped area. The share of Uttar Pradesh to all India gross cropped area is 14 percent but its share to all India consumption of NPK is 17 percent. Farmers are continuously applying generalized quantities of N, P and to some extent Zn and as a consequence, deficiencies of K and other nutrients are spreading in space and time. The intensity of nutrients (N +P_2O_5 + K_2O) use through fertilizers in Uttar Pradesh is 149.6 kg ha^{-1} consisting of 109.6 kg N, 32.7 kg P_2O_5 and 7.3 kg K_2O with N:P_2O_5:K_2O use ratio of 16.0:5.3:1. The share of potash to total NPK consumption is only 5 percent.

In general, N and P additions are greater than their removal by different crops and as a result the apparent balances of both the nutrients are tending to be positive (Table 2). However, the total K removal by major crops is reported to be 1.842 mt against total addition of 863 thousand tonnes through fertilizers and other sources and resulted in a negative K balance of 979 thousand tonnes thereby raising serious concerns of K depletion from the soil. Owing to severe losses of N through leaching and volatilization in the rhizosphere and also through severe denitrification losses in rice soils, the existing positive N balances in the state may not be considered as satisfactory input-output relations and therefore it may be inferred that the current practices of cropping and nutrient management are exhaustive in terms of N and K withdrawals, leading to greater depletion of N and K from native soil reserves. Therefore, appropriate N and K management practices have to be followed in order to minimize the losses to soil fertility and sustain the crop productivity in years to come.

Nutrient balance scenario in major states of southern India

Andhra Pradesh

Andhra Pradesh is one of the most progressive states with respect to agricultural development, maintaining higher levels of crop production compared to several other states. It is the second largest fertilizer consuming state in the country, next to Uttar Pradesh. During the last decade, the consumption of total fertilizer nutrients increased by 25 percent, from a total of 2.131 mt during 1998-99 to 2.667 mt during 2007-08. All the three nutrients recorded positive growth during the period. The consumption of N, P_2O_5 and K_2O at 1.560, 0.695 and 0.412 mt, during 2007-08 registered an increase of 18.2, 14.7 and 105 percent, respectively, over 1998-99. However, the contribution of K in total NPK consumption was the lowest (15.4 percent) as compared to N (58.5 percent) and P_2O_5 (26.1 percent). NPK use ratio changed significantly from 13 : 6 : 2 during 1998-99 to 4.4 : 2.1 : 1 during 2007-08. Per hectare consumption of total nutrients during 2007-08 was 205.3 kg as compared to 158 kg ha^{-1} during 1998-99 and the state of Andhra Pradesh has the highest per hectare consumption among the major states of southern India. The data pertaining to crop nutrient balance in Andhra Pradesh has been shown in Table 3.

For calculating the nutrient balances, information on nutrient additions through fertilizers and crop removal of nutrients has been taken from FAI (2008), whereas, the nutrient additions through organic sources has been adopted from Singh et al. (2001). The total removal of nitrogen during 2007-08 was 0.506 mt, with the addition of 0.786 mt. Therefore, the N balance in the state was positive (0.281 mt) at the present level of crop production and registered a positive growth

Table 3 Nutrient additions, removal by crops and apparent balance in major states of Southern India

State	Nutrients (000 t)			Mining Index (R/A)
	Additions (A)	Removal (R)	Balance	
Andhra Pradesh (a*)				
N	786.0	505.5	280.5	0.6
P_2O_5	187.1	232.8	-45.8	1.2
K_2O	411.3	708.6	-297.3	1.7
NPK Total	1384.4	1446.9	-62.6	3.6
Karnataka (b*)				
N	790.3	569.2	221.1	0.7
P_2O_5	386.8	295.8	91.0	0.8
K_2O	330.3	734.4	-404.0	2.2
NPK Total	1507.4	1599.4	-91.97	3.7
Tamil Nadu (b*)				
N	543.3	494.8	48.6	0.9
P_2O_5	228.1	230.9	-2.8	1.0
K_2O	304.2	726.1	-421.9	2.4
NPK Total	1075.7	1451.7	-376.1	1.3
Kerala (b*)				
N	93.3	185.6	-92.3	2.0
P_2O_5	42.7	76.9	-34.2	1.8
K_2O	72.3	278.6	-206.3	3.9
NPK Total	208.3	541.1	-332.8	2.6

a* Recent figures of nutrient additions and removals along with efficiency factor and 10% of available potential organic matter considered

b* Nutrient additions through fertilizers only of 37.5 percent (0.073 mt) during the last ten years. The total P removal was 0.233 mt and the total P additions were 0.187 mt resulting in a net negative balance of 0.048 mt. Though there is an improvement in P balance from -0.132 mt during 1998-99 to -0.048 mt in 2007-08, there is still a need to review the fertilizer recommendations and develop effective strategies for P management in order to bring down the negative P balance in the state. K balance was also found to be negative, with a total K removal of 0.709 mt and total K additions of 0.411 mt, and the resultant K use is in a state of net negative balance of 0.297 mt. Although the negative balance has come down from 0.431 mt during 1998-99 to 0.297 mt, there is a need to adopt appropriate K management strategies in order to overcome the existing negative balances. In addition to the major nutrients, Sulphur deficiencies have been reported in light textured, low organic matter containing soils, which are prone to subsequent leaching and among the micronutrients, zinc is the most deficient micronutrient in the entire state. The results indicate that the farmers of the region need to adopt the balanced fertilization strategies in order to keep the nutrient balances at optimum levels.

Karnataka

Karnataka state is bestowed with a wide range of soil and climatic conditions that support myriad species of crops and farming systems. The state has been in the fore-front in terms of adoption of newer agricultural practices and maintaining fertilizer use (116 kg ha^{-1}) at par with the national average of 117 kg ha^{-1}. The total nutrient consumption increased from 1.27 mt during 1999-00 to 1.51mt during 2007-08 and registered an increase of 19 percent in the consumption of total nutrients over the last eight years. The state with 6.5 percent of the country's gross cropped area has 6.7 percent of total fertilizer nutrients consumed in the country, which has come down from 1999-2000 levels of 7.6 percent. The consumption of N and K_2O at 0.79 and 0.33 mt during 2007-08, registered an increase of 16.2 percent and 52.8 percent, respectively, over 1999-2000, and the consumption of P_2O_5 at 0.387 mt recorded a slight increase of 1.3 percent during the period. NPK use ratio changed from 3.2:1.7:1 to 2.4:1.2:1 during the period.

The current nutrient addition through fertilizers was worked out from FAI (2008), which reveals that about 1.51 mt of nutrients were consumed against total removal of 1.6 mt of nutrient by different major crops grown in the state resulting in a negative nutrient balance of 0.092 mt of NPK that is not met through fertilizer applications for the crop year 2007-08 (Table 3). However, considering the nutrient availability of about 0.55 mt (Hegde and Surendrababu 2001) through different organic sources in the state, the negative balance of 0.92 lakh tonnes of nutrients could be considered negligible. However, the negative balance of 0.404 mt of K is a matter of concern in the state and before depleting the K reserves of the soils in the state, there is a need to address this issue through appropriate potassium nutrient management practices.

Kerala

The state of Kerala has net cropped area of only 2.1 m ha and the state produces more than 48 percent of coconut, 97 percent of black pepper and 60 percent of natural rubber in the country. In addition, it has a significant share of India's other plantation produces such as coffee, tea, betel nut, cocoa and cashew, fruits such as banana and pineapple and spices like cardamom, ginger, turmeric, nutmeg and clove. The fertilizer nutrient consumption in the state decreased marginally by 5 percent from 0.219 mt during 1998-99 to 0.208 mt during 2007-08 and as a result, the agricultural productivity of the state showed a continuous decline in recent years. While, the consumption of N at 0.093 mt, registered an increase of 7.27 percent during 2007-08 over 1998-99, the consumption of P_2O_5 and K_2O at 42.7 and 72.3 thousand ton, recorded a decline of 3.4 percent and 17.2 percent, respectively, during the period. Present NPK use ratio of the state is 1.3:0.5 :1. The per hectare consumption of total fertilizer nutrients is 70 kg and is far below the national average of 117 kg ha^{-1}.

From the nutrient balance sheet of Kerala (Table 3), it is quite obvious that the fertilizer usage in the state is not adequate to meet the demand for crop removal. Out of the potential demand of 0.541 mt of fertilizer nutrients, only 0.21 mt is added through fertilizers during 2007-08 and as a result, there is a net negative balance of 0.332 mt, which is to be supplied through additional nutrient inputs in order to overcome excess nutrient mining form the soil. The total K removal by major crops is reported to be 0.279 mt against total addition of 0.072 mt K through fertilizers with a negative potassium balance of 0.206 mt and in consequence the K reserve of the soils of the state has depleted. In addition to this, the micronutrient deficiencies are also becoming widespread at an alarming rate (John et al. 2001). For attaining a sustainable crop production from the state and cater to the needs of the ever growing population, there is a need to create awareness among farmers about the responsible management of plant nutrients through balanced and integrated nutrient management strategies.

Tamil Nadu

Tamil Nadu has 3.4 percent of India's gross cropped area with about 4.8 percent of the total fertilizer consumption of the country. The total consumption of fertilizer nutrients in the state increased from 0.79 mt during 1998-99 to 1.075 mt during 2007-08 and has registered an increase of 36 percent over 1998-99 levels. During the last 8-9 years, the consumption of P_2O_5 and K_2O is more than doubled at 0.228

and 0.304 mt, registered an increase of 56.2 percent and 87.6 percent, respectively. The consumption of N at 0.543 mt, however, increased by only 12.4 percent during this period. Per hectare consumption of total nutrients increased from 152 kg to 178 kg during the period. The NPK use ratio in the state during 2007-08 is 2.0:0.7:1.

The crop nutrient balance of the state generated as per the information given in FAI (2008) reveals that the nutrient additions of nitrogen (0.543 mt) is slightly higher than the removal (0.495 mt), resulting in a positive balance of about 0.049 mt (Table 3). With regard to P nutrition, the removal is slightly higher by 2800 tonnes over the P addition through fertilizers and the resulted net negative balance is quite manageable in the state. However, the balances pertaining to K nutrition was significantly negative. About 0.73 mt of K was removed as against an addition of 0.304 mt and resulted in an alarming negative balance of 0.421 mt. With intensive cultivation at a higher stake in the state, this alarming situation would result in depletion of native K reserves of soils and therefore demands attention of scientists, extension workers and policy makers for taking up appropriate K additions through mineral fertilizers and other available sources.

Nutrient balance scenario in major states of western India

Gujarat

Gujarat having 10.69 million hectares of gross cropped area (31.5 percent irrigated) with cropping intensity of 113 percent is one of the agriculturally important states of Western India. The principal crops grown are groundnut, pearl millet, rice, wheat, maize and cotton. The share of area under food grains to gross cropped area is 36.7 percent. The Consumption of total fertilizer nutrients in the state increased from 0.995 mt during 1999-2000 to 1.623 mt during 2007-08, representing a significant growth of 63 percent, over the last eight years. The consumption of all the three nutrients recorded positive growth with N, P_2O_5 and K_2O at 1.052, 0.425 and 0.146 mt during 2007-08, registered an increase of 69, 43 and 95 percent, respectively, over 1999-2000. The intensity of nutrients (N + P_2O_5 + K_2O) use in Gujarat is 143.6 kg ha^{-1} consisting of 93.1 kg N, 37.6 kg P_2O_5 and 12.9 kg K_2O with N:P_2O_5:K_2O use ratio of 7.3 : 2.9 : 1 . The share of potash in total NPK use in the state is 9 percent.

A wide gap was observed between addition and removal of nutrients as indicated by the total negative balance of 1.16 mt of NPK nutrients (Table 4). The total removal of N during 2007-08 was 0.872 mt, however the addition was 1.053 mt. Therefore, the N balance in the state was positive (0.180 mt) at the present level of crop production. The total P removal was 0.771 mt and the total P additions were 0.425 mt resulting in a net negative balance of 0.347 mt. K balance was also found to be negative, with a total K removal of 1.137 mt and total K additions of 0.146 mt, and the resultant K use is in a state of net negative balance of 0.991 mt. In addition to N and P the removal of K, S and micronutrients by crops is at an alarming rate since supplementation of these nutrients through external sources is not adequate (Patel 2001). These observations indicate that there is an urgent need for better soil management practices for sustenance of soil fertility and productivity.

Table 4 Nutrient additions, removal by crops and apparent balance in major states of Western India

State	Nutrients (000 t)			Mining Index (R/A)
	Additions (A)	Removal (R)	Balance	
Madhya Pradesh (a*)				
N	934.2	1053.2	-118.9	1.1
P_2O_5	471.0	385.8	85.2	0.8
K_2O	168.9	943.9	-775.0	5.6
NPK Total	1574.1	2382.9	-808.8	7.5
Gujarat (b*)				
N	1052.6	872.1	180.5	0.8
P_2O_5	424.5	771.7	-347.2	1.8
K_2O	146.1	1137.4	-991.3	7.8
NPK Total	1623.3	2781.2	-1157.9	10.4
Rajasthan (b*)				
N	705.3	825.1	-119.8	1.2
P_2O_5	260.5	371.1	-110.7	1.4
K_2O	20.9	1014.8	-993.9	48.5
NPK Total	986.7	2211.1	-1224.4	51.1
Maharashtra (b*)				
N	1263.5	1088.1	175.4	0.9
P_2O_5	641.5	683.7	-42.2	1.1
K_2O	420.8	1482.9	-1062.1	3.5
NPK Total	2325.9	3254.8	-928.9	5.5

a* Inputs through fertilizers and organic manures considered. Contribution of BNF deducted for calculating N removal

b* Additions through only fertilizer nutrients considered

Madhya Pradesh

Madhya Pradesh is an agriculturally important state of Western India having 14.66 m ha of net cultivated area of which 28 percent is irrigated. Major soils of the state are alluvial, black, mixed red, red and yellow soils and saline/alkali soils. The principal crops grown are wheat, rice, coarse cereals (maize, sorghum, pearl millet and small millets), pulses (pigeon pea, chickpea and lentil) and oilseeds (mustard, soybean). The share of area under food grains to gross cropped area is 60 percent. The consumption of total fertilizer nutrients in the state increased from 0.99 mt during 1998-99 to 1.3 mt during 2007-08, representing a growth of 31.3 percent, during the last ten years. The consumption of all the three nutrients recorded positive growth. N, P_2O_5 and K_2O at 0.796, 0.43 and 0.076 mt during 2007-08, registered an increase of 38, 12.4 and 183 percent, respectively over 1998-99 levels. The current fertilizer use in the state is only 66.4 kg ha^{-1} consisting of 40.6, 21.9 and 3.9 kg ha^{-1} N, P_2O_5 and K_2O respectively, the $N:P_2O_5:K_2O$ use ratio being 10.5 : 5.7 : 1.0. The share of potash in total NPK use in the state is 5.8 percent.

The total removal of N during 2007-08 was 1.053 mt, with the addition through fertilizers and organic manures of 0.934 mt (Table 4). Therefore, the N balance in the state seems to be negative (0.119 mt) at present level of crop production. P was positively balanced at 0.085 mt, however, the K balance was extremely negative. The total K removal by major crops at current level of productivity is 0.944 mt against total addition of 0.169 mt through fertilizers and organic manures showing a negative balance of 0.775 mt. This wide gap in K removal and addition has impoverished soil's K reserves and thus the magnitude and extent of its deficiency and crop responses to its application are on increase in both time and space. The total negative balance of NPK in the state is amounting to 0.808 mt. Apart from considering nutrient contributions from organic manures, there are considerable quantities of crop residues, forest litters, press mud, poultry manure, biofertilisers etc are also available in the state. Therefore, there is a need for the development of strategies for recycling of available crop residues in order to fulfill the existing nutrient gap.

Maharashtra

Maharashtra, the third largest Indian state occupying 1/10th of the area of the country enjoys varied agro-climatic situations. Black soils with swell-shrink characteristics dominate the soil type along with lateritic, coastal alluvial, saline alkali, mixed red and black soils. The consumption of total fertilizer nutrients recorded an impressive growth of 11.3 percent during 2007-08. Total nutrient consumption increased from 1.46 mt during 1998-99 to 2.33 mt during 2007-08. All the three nutrients recorded positive growth during the period. The consumption of N, P_2O_5 and K_2O at 1.264, 0.642 and 0.421 mt, recorded an increase of 45.3, 62.5 and 113.7 percent, respectively, during 2007-08 over 1998-99. The present NPK use ratio was 3.0:1.5:1 and consumption of total fertilizer nutrients in the state during 2007-08 was 103 kg ha^{-1}.

Removal of N during 2007-08 was 1.088 mt, and addition through fertilizers was 1.264 mt, therefore the N balance in the soils of Maharashtra was positive by 0.175 mt (Table 4). P removal by crops was 0.684 mt and additions through fertilizers was 0.642 mt showing a negative balance of .042 mt. This shows that the P use in Maharashtra was below the recommended levels of application and therefore there is a need to increase P application. There is a wide gap in addition of K to soil and their removal by crops. Although about 0.421 mt of K was added, the removal was very high at 1.483 mt, leaving a negative balance of 1.062 mt of K. Replenishment of S and other micronutrients is almost negligible and widespread multi nutrient deficiencies have been reported in the state (Patil et al. 2001). Therefore, there is a need to improve additions of deficient nutrients in the low consuming areas along with use of organic manures and encouraging retention of crop residues in soil.

Rajasthan

Rajasthan having 19.23 m ha of gross cropped area (31 percent irrigated) is one of the agriculturally important states of Western India. The state is endowed with a large diversity in soils from dune and associated soils to medium black soils. The principal crops grown are pearl millet, maize, coarse millets, pulses, oilseeds, cotton, vegetables *etc*. The share of area under food grains to gross cropped area is 59 percent. A variety of cropping systems are in practice in the state. The current fertilizer use in the state is only 45.5 kg ha^{-1} consisting of 32.5, 12.0 and 1.0 kg ha^{-1} N, P_2O_5 and K_2O respectively, the N: P_2O_5 : K_2O use ratio being 57.4:16.9:1.0. The share of potash to total NPK consumption is only 2.3 percent. The total K removal by major crops is reported to be 1.015 mt against total addition of 0.021 mt K through fertilizers showing negative balance of 0.994 mt and in consequence the K reserve of the soils of the state is continuously depleting.

Based on the nutrients absorbed by the crops and nutrients added through fertilizers, the balance sheet shows negative trend for all the three NPK nutrients (Table 4). There is a requirement of about 0.12, 0.11 and 0.99 mt of additional NPK nutrients to bridge the deficit in the state. Gupta (2001) reported that K mining in Rajasthan is highest followed by N, S, P and Zn. The negative nutrient balance in the state could be bridged through adequate use of fertilizers. There is a need to double the present levels of nutrient consumption through additional fertilizer use and also by supplying nutrients through cattle manure and other organic sources.

Conclusions

From the foregoing discussions, it is conspicuous that the nutrient use pattern in majority of the agriculturally important states of India is inadequate and mostly dominated by NP fertilization. The negative balance of K is highly predominant in almost all the states, which imply that the use of K fertilizers is neglected in most cases. K additions through the prevailing practices of manuring and residue recycling, as well as the meager inputs through K fertilizers are not sufficient to match the K removal by different crops and therefore, tremendous efforts are needed to promote K consumption through use of K rich fertilizers. The current trends of nutrient balances reveals that the gap between nutrient use and supply in farming areas will continue to grow wide on account of intensive cropping and therefore, there is a need to ensure proper and timely supply of major as well as secondary and micronutrients. Other than additions through fertilizer nutrients, practices like recycling of crop residues instead of taking back the residues away from the field and use of animal manures through appropriate composting processes should be encouraged than diverting the resources for fuel and other secondary purposes.

Nutrient balance calculations, sometimes, do not give the real picture as they consider nutrient removal by crops and addition through fertilizers neglecting contribution from sources other than fertilizers such as organic manures, crop residues and stubbles, irrigation water etc. Therefore, contribution of nutrients from the available sources should be taken into account while making calculations to the maximum extent possible. Further, if the average use efficiency of fertilizers (N 50-60 percent; P 15-25 percent, K 60-70 percent) is taken into account, the nutrient additions through fertilizers is much more reduced and therefore, the removal exceeds the consumption and nutrient gap is widened. Nevertheless, the situation is balanced by addition of the nutrients through biofertilisers, FYM, compost, green manuring or addition of crop residues in the field. The consumption data on secondary and micronutrient fertilizers are not available. There is a need to compute nutrient balances with respect to secondary and micronutrients, giving emphasis primarily to the most limiting nutrients like S, Zn and B.

References

Aulakh MS, Bahl GS (2001) Nutrient mining in agro-climatic zones of Punjab. Fert News 46 (4): 47-61

Brar MS (2004) Potassium mining and agricultural sustainability: Punjab Scenario Fert News 49 (7): 51-55

FAI (2008) Fertilizer statistics. Fertiliser Association of India, New Delhi

Gupta AK (2001) Nutrient mining in agro-climatic zones of Rajasthan. Fert News 46 (9): 39-46

Hegde DM, Sudhakar-Babu SN (2001) Nutrient mining in agro-climatic zones of Karnataka. Fert News 46 (7): 55-72

ICAR (2008) From the DG's desk. News Reporter (April-June 2008), pp 2

John PS, George M, Jacob R (2001) Nutrient mining in agro-climatic zones of Kerala. Fert News 46 (8): 45-57

NAAS (2006) Low and declining crop responses to fertilizers. Policy Paper 35**:** 1-8

Patel KP (2001) Nutrient mining in agro-climatic zones of Gujarat. Fert News 46 (5): 41-55

Patil VD, Pholane LP, Adsul PB (2001) Plant nutrient mining in agro-climatic zones of Maharashtra. Fert News 46 (7): 43-54

Rao KV (2009) Site-specific integrated nutrient management – principles and strategies. In: Proceedings of the Workshop on SSNM in Rice and Rice-based Cropping Systems*,* Hyderabad, pp 22-29

Singh HP, Sharma KL, Ramesh V, Mandal UK (2001) Nutrient mining in agro-climatic zones of Andhra Pradesh. Fert News 46 (8): 29-42

Vinod K, Antil RS, Narwal RP, Kuhad MS (2001) Nutrient mining in agro-climatic zones of Haryana. Fert News 46 (4): 81-92