J. Plant Nutr. Soil Sci. 2013, *000,* 1–14 **DOI:** 10.1002/jpln.201200253

Review

Potassium management in rice–maize systems in South Asia§

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Abstract

Potassium (K) availability in soils is largely governed by their mineralogical composition. The extent of weathering of primary K-bearing minerals, the chemical pathways through which weathering takes place, as well as the dynamic equilibrium between various K fractions in soils are factors which determine different soil types of varying K-supplying capacity. The marked variability of K availability in soils in South Asia needs to be taken into account when formulating K-management strategies in intensive cereal-based systems in response to K application. Evidence from long-term fertilizer experiments in rice–rice (R-R) or rice–wheat (R-W) systems strongly indicates significant yield responses to K application and negative K balances where K application is either omitted or applied suboptimally. However, K-fertilizer recommendations in South Asia are generalized over large areas while farmers neglect K application to crops and remove crop residues from fields. These practices may strongly affect yield and soil K-fertility status in the emerging rice–maize (R-M) systems in different locations of South Asia. The dry-matter yield of the R-M system is usually much higher than that of the R-R or R-W system causing high withdrawal of nutrients from the soil. The current review assesses various K forms and K availability in diverse soil types of South Asia supporting rice-based systems. Aspects considered include: long-term crop yield and its response to added nutrients, K balance for intensive rice-based systems, and the role of crop residues in supplying K to crops. Emerging data from either completed or on-going experiments on the R-M systems in India and Bangladesh have revealed very high system productivity and variable responses and agronomic K-use efficiency of maize and rice. Potassium responses of maize are extremely high and variable for soils in Bangladesh. Finally, a plant-based strategy for field-specific nutrient management is presented and the need for models and decision support systems for developing efficient K management of the R-M system is also discussed.

Key words: DSS / *Oryza sativa* / potassium-use efficiency / soil fertility / South Asia / *Zea mays*

Accepted March 2, 2013

1 Introduction

Potassium (K) is one of the 17 essential elements for plant growth and development. Plants need large quantities of K, as much as, or even more than nitrogen (N). Potassium plays a key role in many metabolic processes in the plant. Plants deficient in K become susceptible to drought, excess water, high and low temperature, and to pests, diseases, and nematodes. It has been widely reported that most soils of South Asia have high K status due to continuing K additions from rainfall, irrigation water, and release from K-rich clay minerals (*Dobermann* et al., 1996a, b; 1998). Rice–rice (R-R), rice–wheat (R-W), and rice–maize (R-M) are the main rice-based cropping systems practiced on a range of soil types in South Asia. Rice–wheat systems are extensive in the subtropical areas of the Indo-Gangetic Plain (IGP) of South Asia and in China (*Timsina* and *Connor,* 2001) while R-M systems have potential in all climates ranging from tropical to subtropical to warm temperate regions of Asia (*Timsina* et al., 2010, 2011). Rice–rice systems prevail in the irrigated areas of eastern and southern India and in Bangladesh. Several studies have shown that intensive rice-based systems can cause heavy depletion of soil K (*Dobermann* et al., 1996a, b, 1998; *Bijay-Singh* et al., 2004; *Yadvinder-Singh* et al., 2005a). Withdrawal is especially large in these systems because straw is often harvested along with grain (*Timsina* and *Connor*, 2001). Recent soil tests now show that many soils of the IGP of South Asia are becoming K-deficient despite originally high K contents (*Dobermann* et al., 1998; *Bijay-Singh* et al., 2004; *Singh* et al., 2012). Depletion of soil nutrients, particularly K, has been considered as a possible cause of yield decline of rice and wheat in long-term R-W experiments (LTEs) in the

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§ This article is based on a talk at the 12th International Symposium on Management of Potassium in Plant and Soil Systems in China, Chengdu, Sichuan, China, July 24–27, 2012.

IGP of South Asia (*Ladha* et al., 2003; *Bhandari* et al., 2002; *Regmi* et al., 2002a, b).

Rice–maize systems are vital for meeting food requirements and improving food security for a large number of urban and rural poor of South Asia. While there is a large body of literature on nutrient dynamics, including K dynamics, of the R-R and R-W systems, such literature for the R-M systems is scarce. *Timsina* et al. (2010) recently reported the current status, future prospects, and research priorities for nutrient management in R-M systems in South Asia. They concluded that the nutrient demand of the R-M system is very high because high-yielding rice varieties and maize hybrids are cultivated that have high nutrient demand. *Buresh* et al. (2010) also reported that K demand of the R-M system is high due to use of high-yielding maize hybrids in the system. High nutrient demand is associated with high extraction of nutrients from soils, which leads to declining fertility unless the extracted nutrients are replenished from external sources. This scenario is particularly true for the R-M systems where residues of both crops are generally removed from fields aggravating soil-fertility depletion, especially that of K.

The principles of K requirement, and hence K-fertilizer recommendations, are fairly similar for rice, wheat, and maize. Hence, the current review includes some findings for the R-R and R-W systems, and then presents results from some experiments on the R-M systems in India and Bangladesh. The presentation of findings for the R-R and R-W systems is necessary to develop K-management principles for the emerging R-M systems in South Asia.

2 Forms and availability of potassium in soils

Potassium in soil exists in four pools: (1) the soil solution K (K_{sl}); (2) the exchangeable K (K_{ex}); (3) the fixed or nonexchangeable K (K_{nex}); and (4) the K in the lattice of certain primary minerals (K_l), all of which are in dynamic equilibrium. The amount of K_{sl} and K_{ex} is usually a small fraction of total K (1%–2% and 1%–10%, respectively) but is most readily available to plants; the bulk of soil K exists in K-bearing K_{nex} and K_l pools that are less readily available to plants (*Bijay-Singh* et al., 2004). The amount of K present in the soil solution is often smaller than the crop requirement for K and may need continuous renewal for adequate nutrition of high-yielding varieties of cereals. Hence, K nutrition of crops is a function of the amounts of different forms of K in soil, their rates of replenishment, and the degree of leaching (*Bijay-Singh* et al., 2004). The amount of K in each pool varies and depends on the past cropping history, past fertilizer and manure use, and soil water content. Potassium present in micas and feldspars (mineral-matrix K) is very slowly released by weathering and is not adequate to supply the needs of modern crop cultivars with a large yield potential. Nevertheless, it may be important for long-term K balance of cropping systems.

Johnston and *Mitchell* (1974) and *Syers* (1998) showed that the release of K from the nonexchangeable pool is linearly related to the content of initial K_{ex} and there is a close inverse relationship between the decrease in K_{ex} and the release from the K_{nex} pool. Much current evidence suggests that K_{ex} is a good indicator of the likely response of crops to application of K. However, crops with a poor root system that does little to explore the soil for nutrients will have a lower critical K_{ex} value and respond more to K fertilization than crops with a dense root system. *Johnston* and *Krauss* (1998) showed that the K_{nex} as well as residual K from past applications act as a reserve for K released from weathering of soil minerals.

Potassium availability in soils is largely governed by their mineralogical composition. Thus, K fertility of soils can be defined with greater precision by a more detailed understanding of the mineralogy of soil K, forms of K, and different kinds of K transformations occurring in the soil (*Bijay-Singh* et al., 2004). *Sekhon* et al. (1992) reported that illite was the dominant clay mineral in a soil series of the NW IGP spread over Punjab, Uttar Pradesh (UP), and Bihar, containing 39–70 mg kg^{-1} K_{ex} whereas in two soils from the lower Gangetic Plain in West Bengal (WB) smectite and kaolinite were the dominant clay minerals, with K_{ex} values of 87 and 27 mg (kg soil)$^{-1}$, respectively. The effect of clay mineralogy was also very striking in influencing the K_{nex} content of the soils. The two soils from WB contained only 601 and 98 mg kg^{-1} K_{nex}, whereas all the remaining six soil series showed K_{nex} varying from 1330 to 2200 mg (kg soil)$^{-1}$. Trends in total K content were also similar to those for K_{nex}, with minimum total K content in soils from WB. These workers also reported that total K in alluvial soils of the IGP in India ranges from 1.23% to 2.75% while the K_{ex} content ranges from 78 to 273 mg (kg soil)$^{-1}$.

The extent of weathering of primary K-bearing minerals and the chemical pathways through which weathering takes place as well as the dynamic equilibrium between different K fractions in soils are together responsible for the development of different soil types of varying K-supplying capacity in South Asia. Currently, the major unknown factor is what proportion of the total K requirement of a growing crop is supplied from the K_{nex} pool. *Mukopadhyay* and *Datta* (2001) observed that although continuous cropping without K applications decreased the available K from 166 to 85 kg ha^{-1} in the Punjab soils there was still no response to applied K because 90% of the crop K demand was met by K released from the K_{nex} pool. Similarly *Naidu* et al. (2011) also showed that the K_{nex} can contribute significantly to total crop K uptake and there may be no response to added fertilizer K when soils rapidly release K from nonexchangeable sources. *Kinekar* (2011) reported that, for 371 districts of India analyzed for K, 76 districts (21%) were low (< 130 mg kg^{-1}), 190 (51%) medium (130–335 mg kg^{-1}), and 105 (28%) were high (> 335 mg kg^{-1}) in available K. *Srinivas Rao* et al. (2010, 2011) grouped the various districts of India into nine categories, considering different combinations of K_{ex} and K_{nex} pools, and suggested different K-management strategies for each of these categories. *Subba Rao* et al. (2001) reported findings from 29 soil series, all red and lateritic soils low in available and reserve K. Illite-dominated alluvial soils were medium in available but high in reserve K, whereas vertisols containing smectite clay were high in available but relatively low in reserve K. *Naidu* et al. (2011) reported that in most soils of India, there is negative K balance and these soils are now undergoing K depletion varying in magnitude. *Samra* and *Swarup* (2001) observed that intensive cropping over a long period reduced the K_{ex} to a minimum level at which stage release of K_{nex} began. They further concluded that contribution of the K_{nex} towards total K removal was above 90% in the absence of applied K while it was less than 80% with K fertilization. Under intensive cropping, a concentration gradient is set up between the high concentration of K in the unexpanded region of the clay lattice and the K-depleted and expanded part of the clay.

Soils of Bangladesh contain K_{ex} as low as 0.1 to 0.9 meq (kg soil)$^{-1}$ in the Barind tract (*Saleque* et al., 1998) to as high as 1.7 to 4.3 meq (kg soil)$^{-1}$ in the Ganges floodplain (*Saleque* et al., 1990, 2009). In the R-M system–practicing areas in NW and Central Bangladesh, the K_{ex} content ranges from 1.5 meq (kg soil)$^{-1}$ in Comilla to 3.2 meq (kg soil)$^{-1}$ in Rangpur (Timsina, unpublished data). Exchangeable-K content is generally higher in the R-W- and R-M-practicing areas in central western districts of Jessore and Jhenaidah (0.7–3.9 meq [kg soil]$^{-1}$). The K_{ex} ranges from 0.3 to 1.4 and from 0.9 to 6.9 meq (kg soil)$^{-1}$ in saline areas of Barisal and Khulna, respectively, where farmers have started to grow winter maize (Timsina, unpublished data).

The growth environment of crops has a profound effect on K nutrition of R-M systems. Soil-solution K is kept at relatively high levels in flooded rice soils because large amounts of soluble Fe^{2+}, Mn^{2+}, and NH_4^+ ions brought into solution displace cations from the clay complex, and K_{ex} is then released into the soil solution. The displacement of K from the exchange complex, however, ceases on return to aerobic conditions prevalent during maize planting. In fields with adequate drainage, K and other basic cations are then lost *via* leaching. Leaching losses of K can be substantial in highly permeable soils with low cation-exchange capacities. *Yadvinder-Singh* et al. (2005b) found that leaching losses of K were 22% and 16% of the applied K, respectively, in sandy loam and loamy soils maintained at submerged moisture regimes. For Bangladesh, such losses can be as high as 0.1–0.2 kg K ha^{-1} d^{-1} (*Timsina* and *Connor,* 2001). Despite often having a relatively large total K content, the K nutrition of R-M systems grown on the soils of South Asia is not assured, because many heavy-textured alluvial floodplain Terai soils of Nepal and northern and eastern India, and soils of Bangladesh contain vermiculite, illite, or other K-fixing minerals (*Dobermann* et al., 1996b, 1998).

3 Potassium balance in long-term experiments on rice-based systems

Long-term experiments (LTEs) on major cropping systems practiced in major agro-ecological zones (AEZs) or predominant soil types are useful for understanding yield trends, determining changes in soil physical and chemical properties, estimating nutrient balances and identifying the causes of increase or decline in yield over time. Several of such LTEs exist in India, Bangladesh, and Nepal, some for more than 40 years. Results of LTEs currently being conducted in India under the All India Coordinated Research Project on Cropping Systems (AICRP-CS) show progressive increase in response to K fertilizer in both rice and wheat in R-W with greater response in rice (*Subba Rao* et al., 2001). On most soils, including those with illites as dominant clay minerals, K uptake by crops even at recommended NPK doses is far in excess of fertilizer K applied, indicating inadequate K application and much greater exploitation and depletion of native soil K reserves (*Subba Rao* et al., 2001; *Tiwari* et al., 1992; *Samra* and *Swarup*, 2001). By citing the work of *Yadav* et al. (1998), *Subba Rao* et al. (2001) reported that, for 11 cropping systems studied under AICRP-CS, K application ranged from 0 to 100 kg ha^{-1} while the removal ranged from 168 to 483 kg ha^{-1}. For an LTE on R-W in the Punjab, *Bhandari* et al. (2002) also concluded that N and K depletion collectively contributed to a decline in yields of both crops and that increased K input would be required to maintain soil K above sufficiency level and to maintain yields. Likewise, for the R-R system, too, there has been a gradual increase in the magnitude of K response over years in locations where there was negative response in initial years. In another set of LTEs conducted over 30 years in different AEZs with diversified cropping systems and soil types, different crops showed significant responses to K application, the effects being more pronounced in Alfisols and acidic Inceptisols (*Samra* and *Swarup*, 2001). After several years of intensive cropping, response to K application occurred even in alluvial soils dominated by K-bearing illites. On some soils, crops responded to K only after a few years of cropping because of a wide spatial K distribution and its exploitation by roots whereas on other soils yield declined from the beginning.

In an LTE on a rice–rice–wheat system conducted over 30 years in Bhairahawa, Nepal, the yield of the first rice crop, fertilized with recommended NPK fertilizers or farmyard manure (FYM), declined by an average of 0.09 t ha^{-1} y^{-1} and wheat yield declined by 0.05 t ha^{-1} y^{-1}. This was because the available K content of soil declined and the apparent K balance showed net losses of 63.2 and 15.2 kg K ha^{-1} y^{-1} with NPK and FYM treatments, respectively. The yield of the second rice crop, however, did not decline after 20 years due to increased P and K availability under continuous submergence during the monsoon season when the second rice was grown (*Regmi* et al., 2002b). In another LTE on R-W also in the same location, yields of both crops declined with time and both crops responded to K application, but there was a substantially higher response of wheat (*Regmi* et al., 2002a). These studies suggest that depletion of native soil K and inadequate K fertilization are the main reasons for declining yields of the first rice and wheat in the first LTE and that of wheat in the second LTE.

In an LTE on R-R at Gazipur in Central Bangladesh, *Miah* et al. (2008) reported that rice grain yield decreased sharply in a clay-loam soil from about 10 t ha^{-1} in 1985 to 6.2 t ha^{-1} in 2000 in the K omission plots while K application at 50 kg ha^{-1} resulted in positive K balance and maintained yield of both rice crops. In another LTE on R-W in sandy-loam soil in NW Bangladesh, 54 kg K ha^{-1} were needed to maintain positive K balance and yield levels of both crops (*Miah* et al., 2008). In another study also on R-W in NW Bangladesh (*Miah* et al., 2008), application of 54 kg K ha^{-1} increased average grain yield of rice and wheat by 25%–30% and 53%–86%, respectively, across a range of demonstration plots in farmers' fields. Crop-residue incorporation alone increased grain yield of both crops by 20%–21% in K omission plots.

Maize hybrids grown in the winter season in Bangladesh have an attainable grain yield of about 10–12 t ha^{-1}, with similar amount of non-grain biomass. To obtain such high yields, maize plants generally take up around 200 kg N, 30 kg P, 167 kg K, and 42 kg S ha^{-1}. Farmers, on the other hand, apply imbalanced fertilizers, with a high amount of N and low amounts of P, K, S, and micronutrients. In the R-M system in Bangladesh, the apparent nutrient balances have been highly negative for N and K (–120 to –134 and –80 to –109 kg ha^{-1}, respectively), while the P balance has been positive (15 to 33 kg ha^{-1}; *Ali* et al., 2009). Other nutrient depletion–replenishment studies in the R-W systems in Bangladesh have also shown negative balances for N (*Timsina* et al., 2006) and K (*Panaullah* et al., 2006) but positive balance for P (*Saleque* et al., 2006).

A 5-y experiment on the rice–soybean–rice, soybean–rice–maize, and rice–rice–maize systems with seven combinations of N, P, K, and FYM in the Red River Delta in northern Vietnam showed that K was the most yield-limiting nutrient and that regular K applications were required to make investments in the application of other mineral nutrients profitable. In the absence of K application, the average yield gap for rice ranged from 1.2 to 2.2 t ha^{-1} depending on season. For soybean and maize, the yield gap resulting from K omission averaged 0.9 and 3.4 t ha^{-1}, respectively. The application of FYM increased grain yield and K balances more in upland crops than in rice (*Mussgnug* et al., 2006).

The results from various LTEs on intensive rice-based systems suggest that K in all the LTE sites is continuously being mined resulting in negative balance and that fertilizer K recommendations for crops should take into consideration the nonexchangeable fraction of soil K.

4 Role of crop residues in potassium supply to crops

Crop residues contain large quantities of K, and their recycling can markedly increase K availability in soils (*Chatterjee* and *Mondal*, 1996; *Sarkar*, 1997). Recycling of crop residues can improve crop yields at low rates of K application and can decrease crop response to applied K. *Yadvinder-Singh* et al. (2004) reported that release of K from rice straw occurred at a fast rate, and available soil K content increased from 50 mg (kg soil)$^{-1}$ in the untreated control to 66 mg (kg soil)$^{-1}$ in straw-amended treatments within 10 d after incorporation. *Tiwari* et al. (1992) also reported that most of K in the rice residue was released in less than 41 d while *Sarkar* (1997) concluded that the amount of K released from organic materials in the first month was highly correlated with the water-soluble K. *Mishra* et al. (2001) reported that about 79% of total K in rice straw was mineralized within 5 weeks after incorporation and 95.3% by the end of 23 weeks. *Yadvinder-Singh* et al. (2010) reported that 85%–88% of K from buried rice residue had been released at maximum tillering while more than 97% at the end of the decomposition cycle during the wheat season. In contrast, release of K from surface-retained residue averaged about 76%. Thus, rice residues can supply a substantial amount of K to the succeeding wheat or maize.

To understand better the K response under different tillage- and residue-management situations, we analyzed data from a field experiment conducted from 2007/08 to 2009/10 at Modipuram (29°4′ N, 77°46′ E) in NW India to investigate three methods of tillage and crop establishment. The tillage methods were: transplanted puddled rice followed by conventionally tilled maize, (TPR-CTM); conventionally tilled direct-seeded rice followed by CTM, (CTDSR-CTM); and zero-tilled DSR followed by zero-tilled maize (ZTDSR-ZTM). There were two rates of K (0 or 62 kg K ha^{-1}) together with two residue levels, the residues of both crops being either fully

Table 1: Response of rice and maize (kg ha^{-1}) to K application with different crop-establishment practices and residue management options under R-M system. PDFSR, Modipuram, India (2007/08–2009/10).

Crop establishment technique	Response to K		Mean response to K
	residue removed (–R)	residue retained* (+R)	
Rice			
TPR-CTM§	830	390	610
CTDSR-CTM	630	260	445
ZTDSR-ZTM	450	210	330
Mean K response	637	287	462
Maize			
TPR-CTM	920	550	735
CTDSR-CTM	510	310	410
ZTDSR-ZTM	430	250	340
Mean K response	620	370	495

* In TPR-CTM, maize residue was incorporated before rice transplanting.
§ TPR = transplanted puddle rice, CTDSR = conventional-till, direct seeded rice, ZTDSR = zero-till, direct-seeded rice, CTM = conventional-till maize, ZTM = zero-till maize

removed or partially retained with 5 t residue ha^{-1} of each crop on the surface. The soil of the experimental site was a Typic Ustochrept sandy loam with a medium level of soil K_{ex} (113 mg [kg soil]$^{-1}$) content. Mean rice yield response to K of the residue-management treatments was highest with TPR-CTM (610 kg ha^{-1}) compared with responses under CTDSR-CTM and ZTDSR-ZTDSM (Tab. 1). Mean yield response to K of the residue-management treatments of the succeeding maize was 735, 410, and 345 kg ha^{-1}, respectively, for the three tillage and crop-establishment methods. Mean K response for rice and maize was comparatively higher for residue removal (623 to 637 kg ha^{-1}) than residue retention (287 to 370 kg ha^{-1}). Growing DSR also had a pronounced effect on K response of succeeding CTM. Compared with TPR-CTM, maize yield response to K after DSR declined by 43.6% and 44.6% in the residue-removed and residue-retained plots, respectively. Despite residue retention there was still reasonable K response under all tillage and crop-establishment systems indicating that K released from soil and applied as K fertilizer was not enough to meet crop demand.

Buresh et al. (2010) reported that for R-M with 5 t ha^{-1} rice and 12 t ha^{-1} maize yield, the retention of maize residues can markedly reduce the net K export but does not eliminate the deficit in K balance when rice residues are not retained. Retention of all maize and rice residues is required to achieve near-neutral K balances. The R-M system of South Asia with much higher maize yield than wheat or rice yield in the winter season is more extractive of nutrients, particularly K, than R-R or R-W. Hence, residue retention is necessary to sustain the soil fertility and productivity of the R-M systems. Nevertheless, since farmers in South Asia generally remove residues from their fields, modest rates of K fertilizer together with some crop residues need to be applied to optimize K nutrition and to prevent K mining from the soil.

Bijay-Singh et al. (2008) have proposed a simplified “decision tree” to illustrate guidelines for managing residues in rice-based cropping systems. They suggest that for the systems in which residues from rice or a nonflooded crop are retained or incorporated to ensuing rice, the management of the residues depends upon whether the soil was puddled during the recipient rice crop. For the nonpuddled rice production, they recommend a no-till system in which the residues are left on the surface as mulch. For puddled rice production, where crop residues can not readily be used as mulch, however, the residue of the preceding maize crop can typically be safely removed from the field without any loss in productivity or sustainability of the system. However, an appropriate increase in fertilizer addition, particularly K, is required to compensate for nutrient removal in the residues.

5 Rice–maize systems

This section presents grain-yield response and agronomic use efficiency of K of rice and maize in four experiments on R-M systems in India and Bangladesh. Two experiments in India were conducted in several farmers’ fields in Sabour, Bhagalpur, Bihar, and in Bangalore, Karnataka; a further experiment was carried out at the research station in Sabour, Bhagalpur. In Bangladesh, one experiment was carried out in several farmers’ fields in three districts of the country.

5.1 On-farm trials in Bhagalpur, Bihar, India

Twelve on-farm trials were conducted during 2006–07 in Sabour, District Bhagalpur (25°15′ N, 87°1′ E) of Bihar state. Four treatments were compared: (1) farmers’ fertilizer practice (FFP); (2) FFP + 62 kg K ha^{-1} (FFP + K_{62}); (3) FFP + K_{62} + 40 kg S ha^{-1} + 5 kg Zn ha^{-1} (FFP + K_{62} + S_{40} + Zn_5); (4) FFP + S_{40} + Zn_5. The same rate of K was applied to both crops while S and Zn were applied to rice only. The average use of fertilizer by farmers (FFP) of the locality was 80 kg ha^{-1} N and 23 kg ha^{-1} P in rice and 100 kg ha^{-1} N and 23 kg ha^{-1} P in maize while K application was negligible. Inclusion of K in the FFP significantly ($P \leq 5\%$) increased rice yield by 1.8 t ha^{-1} while such increase due to K application over FFP + S + Zn was 3.02 t ha^{-1} (Tab. 2). Although the information on conjoint use of K, S, and Zn in rice in farmers’ field is not available in the Indo-Gangetic Plain (IGP), several on-station studies have revealed the pronounced effect of deficient macro- and micronutrients on rice productivity (*Singh* et al., 2008). The significant increase in rice yield due to K application observed in this experiment is in contrast to an earlier assumption that the release of native K from illitic clay minerals of the soils of the IGP is sufficient to meet the K needs of the crops (*Bijay-Singh* et al., 2004). These results, however, corroborate findings from recent on-station studies conducted under the aegis of the AICRP-CS at seven locations on the

Table 2: On-farm productivity of rice, maize, and R-M system as influenced by SSNM under R-M system at Sabour, Bhagalpur, Bihar.

Treatment	Rice yield / t ha^{-1}	Increase over FFP / %	Maize yield / t ha^{-1}	Increase over FFP / %	System-level maize equivalent yield, SMEY / t ha^{-1}
FFP*	5.21	–	6.75	–	12.49
FFP + K_{62}	7.01	34.55	7.58	12.30	15.31
FFP + K_{62} + S_{40} + Zn_5	8.23	57.97	8.06	19.41	17.13
FFP + S_{40} + Zn_5	6.07	16.51	7.26	7.56	13.95
CD ($P \leq 5\%$)	0.83	–	0.54	–	1.23

* FFP = 80 kg ha^{-1} N and 23 kg ha^{-1} P in rice and 100 kg ha^{-1} N and 23 kg ha^{-1} P in maize; data are means of 12 farmers fields (*AICRP-CS Report*, 2007–10).

Table 3: Changes in soil N, P, K, S, and Zn content (mg kg^{-1}) due to K, S, and Zn application after one R-M cycle at Sabour, Bhagalpur, Bihar.

Treatment	Available N		Available P		Exchangeable K		Extractable S		DTPA-Zn	
	after 1 RM cycle	change over initial*	after 1 RM cycle	change over initial*	after 1 RM cycle	change over initial*	after 1 RM cycle	change over initial*	after 1 RM cycle	change over initial*
FFP	119.0	8.0	12.6	0.9	97.3	–5.0	16.3	–2.3	3.8	–0.4
FFP + K_{62}	105.0	–6.0	10.9	–0.8	111.2	8.9	15.8	–2.7	3.6	–0.6
FFP + K_{62} + S_{40} + Zn_5	101.0	–11.0	10.2	–1.5	107.3	5.0	21.5	3.0	4.5	0.3
FFP + S_{40} + Zn_5	108.0	–3.0	12.1	0.4	96.1	–6.2	23.2	4.7	4.5	0.3

* Initial soil contents for KCl-extractable available N, Olsen-P, 1 M NH_4OAc–extractable K, 0.15% $CaCl_2$–extractable S, and DTPA-Zn were 111 mg kg^{-1}, 11.7 mg kg^{-1}, 102.3 mg kg^{-1}, 18.5 mg kg^{-1}, and 4.2 mg kg^{-1}, respectively (*AICRP-CS Report,* 2007–10)

IGP, which showed that the high-yielding cultivars of rice required fertilizer K ranging from 75 to 101 kg ha^{-1} for attaining maximum economic yield (*Tiwari* et al., 2006). Application of 62 kg ha^{-1} K increased ($P \leq 5\%$) maize yield over FFP by 0.83 t ha^{-1} and over FFP + S + Zn by 1.31 t ha^{-1} (Tab. 2). The productivity of R-M, measured in terms of maize equivalent yield for the system (SMEY), increased significantly with K or conjoint use of K + S + Zn. Use of 62 kg K ha^{-1} over FFP produced additional SMEY by 2.82 t ha^{-1} ($P \leq 5\%$). The SMEY with K + S + Zn, on the other hand, was greater (4.64 t ha^{-1}) compared to their application individually. The FFP in R-M as recorded in this study, as well as in earlier surveys (*Dwivedi* et al., 2001), reveals that farmers applied greater than recommended rates of N along with optimum to suboptimum rates of P, but largely ignored the application of other nutrients particularly K which resulted in K mining and increased crop response to K.

Potassium application over FFP decreased initial KCl-extractable soil available N and Olsen-P content by 14 mg kg^{-1} and 1.7 mg kg^{-1}, respectively, after one R-M cycle (Tab. 3). Available N and Olsen-P content also declined as a result of Zn + S application, with higher decline when K + S + Zn were applied. Greater mining of soil N due to increased biomass production and consequently higher N uptake could be the reason for such a decline in available N content. Long-term experiments on R-W support these results as the available N content generally decreased with the inclusion of K along with NP (*Bijay-Singh* et al., 2004).

Soil K_{ex} content improved with K fertilization alone (13.9 mg kg^{-1}) or in combination with S and Zn (10 mg kg^{-1}), whereas a moderate decline in K_{ex} (1.2 mg kg^{-1}) was noticed with S + Zn application over FFP. Available S and Zn contents, averaged across K treatments, were greater for S + Zn and the magnitude of increase over FFP was 6.05 mg kg^{-1} and 0.7 mg kg^{-1}, respectively. Fertilizer K input on the other hand, resulted in significant decline in S and Zn contents after the completion of one R-M cycle (Tab. 3). Application of K or K + S + Zn in R-M enhanced K_{ex} as compared with the initial content, increasing it from 5.0 to 8.9 mg kg^{-1} (Tab. 3). On the other hand, omission of K from fertilizer schedule resulted in a decline of K_{ex} (–5.0 to –6.2 mg kg^{-1}). The apparent differences in K_{ex} content for no-K and +K was 10.0 to 15.1 mg kg^{-1}. The decline in K content under no-K revealed that higher rates of N (> 180 kg ha^{-1}) and optimal to suboptimal rates of P (20–26 kg P) used by the farmers encouraged K mining from soil and adequate input was essential to prevent or at least mitigate this adverse effect of imbalanced fertilizer use. *Tandon* and *Sekhon* (1998) reported earlier that applications of N alone increased K uptake by 57% over control, and N and P applications together increased the K uptake by 145%. The K extraction is especially large in R-W and R-M because straw is often harvested along with grain, for its competitive use as thatching material, fuel, or animal feed, or burnt to facilitate tillage (*Timsina* and *Connor*, 2001). To overcome such K mining, adequate amounts of K fertilizer need to be used.

5.2 On-farm trials in Bangalore, Karnataka, India

On-farm trials (24 each in 2008–09 and 2009–10) were conducted in Bangalore (12°8′ N, 77°37′ E), Karnataka with four treatments (control; 100 kg N ha^{-1}; 100 kg N ha^{-1} and 10 kg P ha^{-1}; 100 kg N ha^{-1} and 35 kg K ha^{-1}; 100 kg N ha^{-1}, 10 kg P ha^{-1}, and 35 kg K ha^{-1}). Results showed that application of recommended doses of NPK (100, 10, and 35 kg of N, P, and K, respectively) to rice produced grain yield of 4.26 and 5.80 t ha^{-1} during 2008–09 and 2009–10, respectively (Tab. 4). Omission of P or K fertilizers caused a yield loss of 0.6 to 0.9 t ha^{-1} and 1.0 to 1.02 t ha^{-1}, respectively. Agronomic response to P and K application was 45.5 to 46.4 and 13.8 to 21.4 kg grain kg^{-1} for P and K, respectively. Similar response to P and K over N alone was 19.1 to 69.5 kg kg^{-1} for P and 7.6 to 26 kg kg^{-1} for K.

Like rice, maize grain productivity was also at a maximum under the plots treated with recommended doses of NPK (6.22 to 7.09 t ha^{-1}). Omission of P or K resulted in significant ($P \leq 5\%$) yield loss of 2.35 to 2.42 t ha^{-1} and 1.82 to 1.93 t ha^{-1}, respectively, over the 2 years (Tab. 4). At these response levels, agronomic efficiency of P and K was 71.2 to 73.3 kg kg^{-1} and 55.2 to 58.5 kg kg^{-1}, respectively. These results agree closely with the recent on-farm study by *Majumdar* et al. (2012) in which yield loss due to omission of K application to rice and maize was of 90–1806 kg ha^{-1} (mean: 622 kg ha^{-1}) and 140–1320 kg ha^{-1} (mean: 700 kg ha^{-1}), respectively. Further, considerable increase in agronomic efficiency of P and K may be visualized as P × K interaction as reported by *Tiwari* (2002), which reveals that efficiency of

Table 4: On-farm yield and agronomic efficiency of N, P, and K in rice and maize under R-M system in Bangalore, Karnataka, India (*AICRP-IFS report*, 2009–11); data are means of 24 farmers' fields in each year.

Treatment	**2008–09**	**2009–10**	**Treatment**	**2008–09**	**2009–10**
	rice yield / t ha^{-1}			maize yield / t ha^{-1}	
Control	2.23	2.50	Control	1.98	2.45
N_{100}	2.94	3.69	N_{150}	2.87	3.49
N_{100} P_{10}	3.36	5.22	N_{150} P_{15}	4.29	5.27
N_{100} K_{34}	3.26	4.78	N_{150} K_{27}	3.87	4.67
N_{100} P_{10} K_{34}	4.26	5.80	N_{150} P_{15} K_{27}	6.22	7.09
CD ($P \le 0.05$)	0.22	0.24	CD ($P \le 5\%$)	0.28	0.2
Agronomic efficiency / kg grain (kg nutrient)$^{-1}$			Agronomic efficiency / kg grain (kg nutrient)$^{-1}$		
N over control	7.1	11.9	N over control	7.9	6.9
P over N	19.1	69.5	P over N	43.0	53.9
K over N	7.6	26.0	K over N	30.3	35.8
P over NK	45.5	46.4	P over NK	71.2	73.3
K over NP	21.4	13.8	K over NP	58.5	55.2

applied P increased with increasing initial available-K status of soils. Responses to P were generally higher in high-K soils followed by medium- and low-K soils. Thus, to obtain full benefit from P fertilization and to maintain high soil K status, adequate K supply should be ensured.

5.3 On-station experiment at Bhagalpur, Bihar, India

Site-specific nutrient-management (SSNM) options (see section 5 for details) for rice and maize in the R-M systems were investigated under on-station experimentation from 2006–07 to 2008–09 at Sabour, Bhagalpur (25°1′ N, 87°1′ E), Bihar. Eight treatments were compared: three levels of P (0, 13, and 26 kg ha^{-1}) and three levels of K (0, 42, and 83 kg ha^{-1}) to both crops; four levels of S (0, 20, 40, 60 kg ha^{-1}) to rice only; and 150 kg N ha^{-1} to both crops. The recommended doses of fertilizer for Bihar state (state recommendation—SR) were 100 kg N, 18 kg P, and 17 kg K ha^{-1} in rice and 120 kg N, 33 kg ha^{-1} P, and 42 kg K ha^{-1} in maize while the average fertilizer used by the farmers (FFP) in the area was 70 kg N, 15 kg P, and 8 kg K ha^{-1} in rice and 100 kg N, 13 kg P, and 17 kg K ha^{-1} in maize (see Tab. 5 for treatment combinations). Initial available N, Olsen-P, exchangeable K, and extractable S of the experimental site were 134 kg ha^{-1}, 31.1 kg ha^{-1}, 185 kg ha^{-1}, and 22 kg ha^{-1}, respectively. The results revealed that application of 150 kg N, 13 or 26 kg P, and 83 kg K to each crop along with 40 kg ha^{-1} S to rice only (SSNM treatments 1 and 2) gave highest productivity of the individual crops and of the system. Comparing these treat-

Table 5: Productivity of rice, maize, and R-M system as influenced by different SSNM options at Sabour, Bhagalpur, Bihar (means over 3 years).

Nutrient rates / kg ha^{-1}	**Rice** / t ha^{-1}	**Maize** / t ha^{-1}	**System-level maize equivalent yield** (SMEY)
N_{150} P_{13} K_{83} S_{40}	7.42	7.99	16.16
N_{150} P_{26} K_{83} S_{40}	7.78	8.55	17.13
N_{150} P_{0} K_{83} S_{40}	6.38	6.91	13.94
N_{150} P_{13} K_{42} S_{40}	7.19	7.72	15.65
N_{150} P_{13} K_{0} S_{40}	6.16	6.71	13.49
N_{150} P_{13} K_{83} S_{60}	7.46	8.18	16.39
N_{150} P_{13} K_{83} S_{20}	6.96	7.65	15.33
N_{150} P_{13} K_{83} S_{0}	6.66	7.49	14.83
State recommendation (SR)*	6.32	7.40	14.37
Farmers fertilizer practices (FFP)	5.03	6.55	12.10
CD ($P \le 5\%$)	0.61	0.67	1.54

* SR = 100 kg N, 16 kg P, and 17 kg K ha^{-1} in rice and 120 kg N, 33 kg ha P, and 42 kg K ha^{-1} in maize; FFP = 70 kg N, 15 kg P, and 8 kg K ha^{-1} in rice and 100 kg N, 13 kg P, and 17 kg K ha^{-1} in maize (*AICRP-CS Report,* 2007–10)

Table 6: N, P, and K uptake in rice, maize, and R-M system as influenced by K fertilization at Sabour, Bhagalpur, Bihar (mean over 3 years). All nutrients were applied both to rice and maize except S which was applied to rice only (*AICRP-CS Report,* 2007–10).

Nutrient rates / kg ha^{-1}	**Rice**	**Maize**	**R-M system**
	N uptake / kg ha^{-1}		
N_{150} P_{13} K_{83} S_{40}	136.8	192.6	329.5
N_{150} P_{13} K_{42} S_{40}	134.9	187.6	322.3
N_{150} P_{13} K_{0} S_{40}	118.9	158.2	277.0
CD ($P \le 0.05$)	15.3	22.3	41.5
	P uptake / kg ha^{-1}		
N_{150} P_{13} K_{83} S_{40}	50.5	63.8	114.3
N_{150} P_{13} K_{42} S_{40}	48.2	58.1	106.3
N_{150} P_{13} K_{0} S_{40}	43.7	55.3	99.0
CD ($P \le 5\%$)	4.7	7.8	11.4
	K uptake / kg ha^{-1}		
N_{150} P_{13} K_{183} S_{40}	178.1	231.1	409.2
N_{150} P_{13} K_{42} S_{40}	159.1	212.9	372.0
N_{150} P_{13} K_{0} S_{40}	135.7	191.2	326.9
CD ($P \le 5\%$)	21.1	20.7	41.4

ments with SR and FFP, the productivity gain of rice, maize, and R-M with SSNM was 1.09, 0.58, and 1.79 t ha^{-1}, respectively, over SR and 2.38, 1.43, and 4.06 t ha^{-1}, respectively, over FFP (Tab. 5). These results corroborate very well with earlier work on the rice-based systems by *Singh* et al. (2011) where the advantages of SSNM over SR and FFP were mainly attributed to a favorable balance and adequate application of limiting nutrients. In the experiments reported here, gradient doses of K application in SSNM brought significant yield gain over no-K application in both crops as well as for the total system of about 16.7% to 20.5%, 15.1% to 19.1%, and 15.9% to 19.8%, respectively. Total N, P, and K uptake increased with increasing K-application rate in rice, maize, and R-M system (Tab. 6). Application of 42 kg K ha^{-1} caused significant ($P \le 5\%$) increase in total uptake of N and K over no-K, and magnitude of increase was 15.1%, 21.6%, and 18.6% for N and 31.2%, 20.1%, and 25.2% for K in rice, maize, and R-M system, respectively. Although the highest N and K uptake were recorded at 83 kg K ha^{-1} K application, this was not significant ($P \le 5\%$) beyond 42 kg ha^{-1}. On the other hand, increase in total P uptake was significant ($P \le 5\%$) only at 83 kg ha^{-1} K application over no-K. These results are in agreement with those of *Kinekar* (2011) who reported that for rice, wheat, and maize the N uptake is 20, 25, and 29.9 kg (t grain)$^{-1}$ while K uptake was 30, 33, and 32.8 kg (t grain)$^{-1}$, respectively. Balanced fertilization with K thus not only increased rice and maize productivity but also helped to mitigate N and P stresses by increasing uptake of these nutrients.

Agronomic efficiency (AE) for P increased in rice, maize, and R-M system with increasing K rates. On the other hand, AE for K declined with increasing K rates (Tab. 7). Recovery efficiency (RE) measured to assess the proportion of total nutrient applied being utilized by the crops also indicated that RE for P was highest at the highest K level while RE for K was highest at the lowest K level. These results are consistent with the results of other experiments, in which recommended NPK fertilization increased annual productivity and fertilizer-use efficiency over N or NP alone (*Swarup* and *Wanjari*, 2000; *Tiwari* et al., 2006).

Application of gradient rates of K exerted a significant influence on various soil-fertility parameters (Tab. 8). Irrespective of treatments, the KCl-extractable available N, Olsen-P, and $CaCl_2$-extractable S contents in soil increased over their initial status after 3 R-M cycles, however, a declining trend was noticed with increasing K rates. Highest contents of available N, Olsen-P, and extractable S were recorded in the no-K treatment where the K_{ex} content was lowest. Greater mining of soil N, P, and S due to increased biomass production and higher uptake of N, P, and S content with +K compared with no-K may be the reason for the decline in soil N, P, and K content. Further, the AE and RE of P were greater when 83 kg was applied along with N, P, and S. Such results indicate that balancing K supply in the fertilization schedule triggers the efficiency of other nutrients (N, P, and S in the present case) and that crops utilize the available nutrients more efficiently. These results are consistent with findings of other workers (*Dwivedi* et al., 2011; *Tiwari* et al., 2006).

Table 7: Agronomic efficiency and recovery efficiency of P and K as influenced by gradient rates of K application under R-M system at Sabour, Bhagalpur, Bihar (mean over 3 years). All nutrient doses were used to rice and maize both except S which was applied to rice only (*AICRP-CS Report,* 2007–10).

Nutrient rates / kg ha^{-1}	**Agronomic efficiency** / kg grain (kg nutrient)$^{-1}$			**Recovery efficiency** / %		
	rice	maize	system	rice	maize	system
	phosphorus					
N_{150} P_{13} K_{83} S_{40}	65.9	82.8	85.5	35.6	72.6	54.1
N_{150} P_{13} K_{42} S_{40}	52.8	62.6	65.9	18.9	29.6	24.3
	potassium					
N_{150} P_{13} K_{13} S_{40}	15.2	15.4	16.1	51.1	48.0	49.6
N_{150} P_{13} K_{42} S_{40}	25.0	24.5	26.0	56.3	52.3	54.3

Table 8: Changes in soil-fertility parameters after 3 years of R-M cropping with variable K rates at Sabour, Bhagalpur, Bihar. All nutrients were used both to rice and maize except S which was applied to rice only.
Initial available N, Olsen-P, 1M NH_4OAc–extractable K, and 0.15% $CaCl_2$–extractable S were 134 kg ha^{-1}, 14 kg ha^{-1}, 154 kg ha^{-1}, 22 kg ha^{-1} (*AICRP-CS Report,* 2007–10).

Nutrient rates / kg ha^{-1}	Available N		Available P		Exchangeable K		Extractable S	
	after 3 R-M cycle / kg ha^{-1}	change over initial / %	after 3 R-M cycle / kg ha^{-1}	change over initial / %	after 3 R-M cycle / kg ha^{-1}	change over initial / %	after 3 R-M cycle / kg ha^{-1}	change over initial / %
$N_{150}P_{13}K_{83}S_{40}$	188.3	40.5	34.7	11.6	207.8	12.3	25.7	16.8
$N_{150}P_{13}K_{42}\ S_{40}$	191.2	42.7	36.4	17.0	198.9	7.5	26.8	21.8
$N_{150}P_{13}K_{0}\ S_{40}$	202.5	51.1	38.5	23.8	188.5	1.9	28.2	28.2
CD ($P \leq 5\%$)	11.8	–	3.0	–	15.1	–	1.0	–

5.4 On-farm trials on SSNM in R-M systems in Bangladesh

SSNM studies on R-M systems have been conducted for the past 4 years in several farmers' fields at three districts in Bangladesh. The District Comilla (23°28′ N; 91°10′ E) lies in the central eastern part while the districts Rajshahi (24°22′ N; 88°39′ E) and Rangpur (25°42′ N; 89°22′ E) lie in NW part of the country. At all sites, winter maize was planted after monsoon rice. In Comilla and Rangpur, the soils were quite acidic (pH 5.6) but those in Rajshahi were slightly alkaline. Organic carbon was higher in Rajshahi (0.88%) than in the other two districts (0.75%–0.78%). Total N in all districts was quite low, with 0.1% in Comilla and 0.06% in the other two districts. Available P in all districts showed relatively higher values (26.7 to 46.8 mg kg^{-1}) than the critical level of 14 mg kg^{-1} for aerobic crops. Exchangeable K in the soils of Comilla and Rajshahi were 0.15 and 0.19 cmol kg^{-1} (more than the critical level of 0.1 cmol kg^{-1} for lowland rice and less than 0.2 cmol kg^{-1} for upland crops) while the Rangpur soils contained a very high level of K (0.32 cmol kg^{-1}).

On-farm omission plot trials on winter maize after rice tested the effect of nutrient omission and reduced doses of P and K on maize yield in all the three districts (Tab. 9). N, P, and K were applied at 255, 74, and 200 kg ha^{-1}, respectively, in the full NPK treatment at all sites. Omission of K decreased maize yield significantly at all sites in both years, with highest reduction in Comilla. The yields were maintained or just slightly reduced by application of a low level of K (≈ 70% of the full rate; Tab. 9). In both years, available K poorly explained the yield of maize in –K treatments (Timsina, unpublished data).

The response of maize to applied N, P, and K varied in both years, and the response was variable among farmers' fields within a district in each year. In 2009–10, there was a more than 3 t ha^{-1} response to K in more than 60% fields in Comilla while such response was only in about 20% fields in the other two districts. In 2010–11, all fields in Comilla and 50%–60% fields in the other two districts showed > 3 t ha^{-1} response (data not shown). Comilla had the lowest level of soil K_{ex} and hence response was highest. In both years, the agronomic efficiency of K (AE_K, kg grain [kg K applied]$^{-1}$) varied widely across districts as well as across farmers' fields within a district. AE_K in the individual fields ranged from 0.2 to 29.4 kg grain (kg K applied)$^{-1}$ in the first and from 0 to 38.3 in the second year. The mean AE_K in the three districts ranged from 4.1 (Rangpur) to 15.4 kg grain (kg K applied)$^{-1}$ (Comilla) in the first and from 10.1 (Rangpur) to 28.2 kg grain (kg K

Table 9: Grain yield (t ha^{-1}) of winter maize grown after rice in omission plot trials, ACIAR R-M and IPNI project sites, Bangladesh.

Treatment*	2009-10			2010-11		
	Comilla ($n = 18$)	Rajshahi ($n = 9$)	Rangpur ($n = 5$)	Comilla ($n = 17$)	Rajshahi ($n = 17$)	Rangpur ($n = 8$)
–K	5.3	7.8	7.5	3.4	6.7	6.0
NPK	8.3	9.3	8.3	9.0	8.8	8.1
NK Low P	8.0	8.2	7.7	8.7	8.0	6.0
NP Low K	7.9	8.5	7.3	9.0	7.7	5.8
N Low PK	7.9	8.8	6.8	8.8	7.7	5.7
CD ($P \leq 5\%$)	0.8	0.6	1.2	0.7	0.5	0.9

* N, P, and K rates for the full NPK treatment are 240, 75, and 199 kg ha^{-1}, respectively. Low P and low K rates are 44 and 141 kg ha^{-1} P and K, respectively.

applied)$^{-1}$ (Comilla) in the second year (data not shown). These results demonstrate high variability in grain yield of winter maize grown after rice across farmers' fields in Bangladesh and also remarkably high yield response to K in all districts, especially in Comilla. Comilla is also the district with the lowest level of exchangeable K and highest agronomic efficiency of applied K. Under these conditions if K fertilizer is not applied to winter maize according to crop demand, a tremendous yield loss will result accompanied by a decline in soil K-supplying capacity, and ultimately unsustainability of R-M systems.

6 Field-specific potassium management

The SSNM approach provides an opportunity to manage nutrients in a spatially and temporally variable manner in a production system. In small-scale production systems in Asia, this translates into managing nutrients in a field-specific manner. SSNM could be implemented through a soil test–based approach or by a plant-based approach where actual crop responses under nutrient limitations are used as indirect estimates of soil nutrient-supplying capacities. In the plant-based approach, *Witt* et al. (1999) used the QUEFTS (QUantitative Evaluation of the Fertility of Tropical Soils) model developed by *Janssen* et al. (1990) to develop the generic relation between grain yield and nutrient accumulation in aboveground biomass and to predict nutrient requirement to achieve predetermined yield goals (*Witt* et al., 1999). They reported that 14.7 kg N, 2.6 kg P, and 14.5 kg K in rice plants would be needed to produce 1 t grain yield of rice (referred to as reciprocal internal efficiencies, RIE) based on 60%–70% of yield potential. These values were subsequently combined with 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). Subsequently, *Buresh* et al. (2010) used several data sets from South and Southeast Asia and reported that 14.6 kg N, 2.7 kg P, and 15.9 kg K in rice plants would be needed to produce 1 t grain yield of rice, also based on 60%–70% of yield potential. *Witt* et al. (2009) also used the SSNM approach for maize in Indonesia, Philippines, and Vietnam. For maize, based on data sets from Nebraska (USA), Indonesia, and Vietnam (*Setiyono* et al., 2010), *Buresh* et al. (2010) reported that 2.56 kg P and 17.4 kg K would be needed to produce 1 t grain yield of maize based on 80% of climate-adjusted yield potential of 14 t ha^{-1}. The K requirements to produce 1 t yield of rice or maize grain as reported by *Witt* et al. (1999) and *Buresh* et al. (2010) are smaller than 19.5 to 38.0 kg K required for rice and 13.2 to 30 kg K required for maize (*Subba Rao* et al., 2001) and 30 kg K for rice and 32.9 kg K for maize (*Naidu* et al., 2011) for different soils and locations of India. Obviously, crop requirement of nutrients to produce one unit amount of grain varies depending on soil, climate, and variety.

Buresh et al. (2010) developed several equations to estimate K balances in agricultural fields and recommended site-specific K-fertilizer rates for single crops as well as cropping systems involving cereals. The essential components of such K-balance calculations included contributions (inputs) from retained residues, irrigation water, and added organic matter, and loss (output) of K from the system through leaching and export through straw and grain of the crops. Farmers in the NW IGP, often use excessive irrigation water, which contains high amounts of K. *Singh* et al. (2012) reported that under intensively cultivated R-W in the NW IGP, the K input through irrigation water was in the order of 85 kg ha^{-1} cycle^{-1}. At the same time, the soils in this area are light-textured and percolation losses are quite high. This means that the potential for loss of K, added through irrigation water and released from K_{nex} pools of minerals, through percolation can also be high. *Buresh* et al. (2010) reported that the K balance can be negative even at an estimated addition of 125 kg K ha^{-1} from irrigation water if only 15% of the residues of both rice and wheat are retained in the field and can be neutral only at 100% retention of rice residues with similar addition of K through irrigation water. This suggests that the K balance in R-W or R-M in South Asia, where the system grain yield can reach 15–20 t ha^{-1} with equivalent amount of non-grain biomass, could be highly negative even with high addition of K through irrigation water. Hence, external addition of K is required to sustain productivity and the high variability in K content in irrigation water and in residue management across the IGP will require site-specific estimation of K balance for the R-W or R-M system.

Witt and *Dobermann* (2004) suggested that expected yield gain from the added nutrient or estimated nutrient balance can be used to determine fertilizer-K requirements to achieve a targeted yield. In the yield-gain approach, the fertilizer K required to achieve a targeted yield is a function of the expected yield gain from the added nutrient, the reciprocal internal efficiency (RIE) for the nutrient, and the use efficiency of the nutrient. Fertilizer-K requirement to achieve a targeted yield can also be estimated through nutrient input–output balances. *Witt* and *Dobermann* (2004) developed equations based on nutrient balance to estimate fertilizer-K requirement for a crop with full maintenance of soil K. A distinctly undesirable feature of fertilizer-K rate determined by the yield-gain approach is higher K depletion at high than at low target yields. *Buresh* et al. (2010) found that fertilizer-K requirement determined by the yield-gain approach increased with increasing target yield but the K rate did not increase sufficiently to prevent increasing depletion of soil fertility with increasing yield. This could accelerate the onset of nutrient limitations and subsequent declines in productivity in existing high-yielding areas. At the same time, the full-maintenance approach can result in relatively large application of K that may not be profitable at no or low yield gain. Thus, they examined two options using nutrient balances to calculate fertilizer-K rates based on partial maintenance with gradual draw-down or depletion, rather than full maintenance of soil K. In the first option, fertilizer-K requirement was calculated as a fraction of full maintenance of the nutrient input–output balance, the fraction to be drawn from soil nutrient reserve. In the second option, depletion of K from soil reserves was allowed up to a threshold limit, which was treated as an input in the nutrient balance. The authors showed that the second option has the risk of higher nutrient depletion and declining productivity at higher yield target. They also combined the partial-maintenance and yield-gain approaches for determining fertilizer-K rate when crop response to K is certain. They showed that when the yield gain due to applied K is relatively small, fertilizer-K requirements can be determined with only a partial-maintenance approach but when yield gain is more pronounced, a partial maintenance–plus–yield gain approach can be considered. *Majumdar* and *Satyanarayana* (2011) and *Sanyal* et al. (2009) reviewed the mineralogy associated with K forms and availability, K uptake and balance, and strategies for K-fertilizer management for rice-based systems in India, including the R-M systems. Acknowledging the work of *Witt* and *Dobermann* (2004) and *Buresh* et al. (2010), they also advocated the use of site-specific K management for rice-based systems in South Asia and particularly for India.

The emerging R-M system offers a major challenge to maintain K balance in the soil. The two major reasons for this are firstly that the ecosystems in which the R-M systems thrive (eastern and southern India, Bangladesh, Nepal, and parts of Pakistan) do not have high K concentration in irrigation water, and secondly retention of residues of rice and maize in the field is not a common practice. Additionally, the dry-matter yield of the R-M system is usually much higher than that of R-R and R-W involving high extraction of nutrients from the soil. In the absence of residue-retention practices, a large amount of K is exported from the field with harvested product and the residues. This strongly suggests that higher K deficits and higher fertilizer-K requirement are to be anticipated in the R-M system.

Finally, improved K management may have great potential for improving the overall productivity of the R-M systems of South Asia, but will require special consideration on soils containing K-fixing minerals. It may be appropriate to make separate applications of K to crops in the R-M systems on non-K-fixing soils, with a lower application of K to rice with the aim of preventing loss by leaching, especially on permeable soils. Finally, occurrence of K deficiency and response to applied K depend on yield level, K buffering capacity of the soil, straw management, and net K inputs from sources other than fertilizer. Clay mineralogy, texture, and K inputs from irrigation or rainwater need to be considered (*Dobermann* et al., 1998) along with K inputs from sediments deposited from flood plains and flood water when formulating a K-management strategy. Application of full-maintenance rate of K (input = output) may not be profitable for rice and maize under situations where crop response to K is poor. In such soils, some K mining may be allowed by applying K below the maintenance rate. However, as discussed above, the extent of mining that could be allowed in a particular soil will require a complete understanding of K dynamics in the soil as well as the K input–output balance associated with the cropping system practiced.

7 Need for models and decision-support systems

Integrated process-based crop, soil, and weather models can dynamically predict crop growth, development, and yield. The decision-support systems for agro-technology transfer-DSSAT (*Hoogenboom* et al., 2004) software, was developed jointly by researchers in several universities in the USA working together with scientists from the developing countries in Asia and Africa. Several crop models are in use including those for rice and maize, which can predict crop yield and can assist in fertilizer management from soil and weather data collected on a daily basis. In the released version of DSSAT (v.4.5), there is capacity to predict N- and P-fertilizer recommendations for most crops. The N and P models within DSSAT have been tested and applied for N- and P-fertilizer recommendations in Asia and Africa. In the unreleased version (v4.6), there is a K model which can predict K uptake from K forms in soil and plant and can provide K-fertilizer recommendations currently for rice and maize (U. Singh, IFDC, Alabama, USA, personal communication). However, the K model has not been evaluated against data sets from field experiments. Once evaluated, it can then be used for K-fertilizer recommendations for rice and maize when grown under single- or multiple-crop systems, such as R-M. In contrast to the complex process-based models, the simple decision-support systems (DSSs) such as “Nutrient Manager” for Rice and Maize developed by R. J. Buresh (at IRRI) and his co-workers and “Nutrient Expert” for Maize and Wheat proposed by The International Plant Nutrition Institute (IPNI), have the potential to estimate K-fertilizer recommendation for R-M systems. Such DSSs could help to reduce the cost of production and increase yield and profit by reducing the fertilizer rates applied to these crops and, because of their simplicity in use, they would also help to extend the fertilizer-management technologies to a large number of farmers over a short period of time. However, to use such DSSs with confidence would require more rigorous work to include soil and plant processes affecting the K forms and releases from different soils, as well as K availability and uptake, and conversion efficiency to grain. Once robust relationships between the different processes are established then the DSSs would require quality data to enable their evaluation for the environments where R-M systems are practiced.

8 Conclusions and research needs

South Asian soils vary in their genesis and mineralogy affecting the exchangeable and nonexchangeable K pools. Besides affecting soil-K availability, the mineralogical composition of soils often influences fixation of K applied as K fertilizer or received from other sources such as crop residues or irrigation water. Potassium recommendations for cereals are often far lower than that required by removal by crops, and farmers seldom apply K fertilizer based on crop requirement. Low external application of K and the common practice of removing cereal residues from fields have led to depletion of K largely from nonexchangeable fractions that are rarely assessed in routine soil tests. Long-term experiments on R-W and R-R in South Asia have highlighted the significant effect of K on crop yields, uptake, and use efficiencies of other essential nutrients, as well as on system nutrient balance and native soil K reserves. Rice–maize systems are emerging rapidly in various locations of South Asia that may be affected by K-availability constraints and result in negative K balance. High-yielding R-M systems have high nutrient demand and may deplete soil K quickly when external supply is limited. Crop-residue removal from fields for competitive uses is common in South Asia and field-specific application of K and retaining some amount of crop residues will be required to maintain and improve crop yield and soil K fertility. Emerging data from either completed or on-going experiments on the R-M systems in India and Bangladesh have revealed very high system productivity and variable responses and agronomic use efficiency of maize and rice to applied K. Potassium responses of maize are extremely high and variable for soils in Bangladesh. Finally, the review presents a plant-based strategy for field-specific nutrient management and fertilizer-K recommendation. This has the potential to effectively balance crop K demand and maintain native K fertility of soils, including the possible use of crop models and DSS for the R-M systems of South Asia.

Acknowledgment

The authors are grateful to *IPI* for inviting the first author to present this paper in the IPI-sponsored international symposium “Management of K in soil-plant systems in China” in Chengdu, China, in July 25–27, 2012.

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