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Analysis of crop productivity, partial factor productivity, and soil fertility in relation to nutrient management in the Indo-Gangetic plains

H Singh • SK Bansal

Abstract The Indo-Gangetic Plains (IGP) is among the most extensive fluvial plains of the world covering several states of the northern, central, and eastern parts of India. The IGP occupies a total area of approximately 43.7 m ha, which is nearly 13% of the total geographical area of the country, and represents eight agro-ecological regions (AER) and 14 agro-ecological sub-regions. Over the last three–four decades the states of the IGP have been successful in increasing their food grain production, chiefly rice and wheat, by introducing high-input technologies to meet the demands of the exponentially growing population. Now IGP produces about 50% of the total food grains to feed 40% of the population of the country. The production of grains is, however, not uniform across the IGP regions because of the spatial variation in land-resource characteristics and socio-economy in the region. Also, the imbalanced fertilizer application in the IGP has resulted in stagnating or declining yields, nutrient use efficiencies, and soil health. The future sustainability of the present cropping system in the IGP demands a review on the trends in crop productivity vis-à-vis potential yields, partial factor productivity, and soil fertility. This paper reviews both the trends and the impact of efficient nutrient management strategies, which can significantly benefit the agriculture in the region through increasing crop yields, adding to farmer's income, and improving agricultural sustainability.

Keywords Crop productivity • Geographic Information System • Indo-Gangetic Plain • nutrient use efficiency • rice • Site-Specific Nutrient Management • wheat

Abbreviations: IGP – Indo-Gangetic Plains; m ha – million hectares, SSNM – Site-Specific Nutrient Management, AER – Agro-Ecological Region

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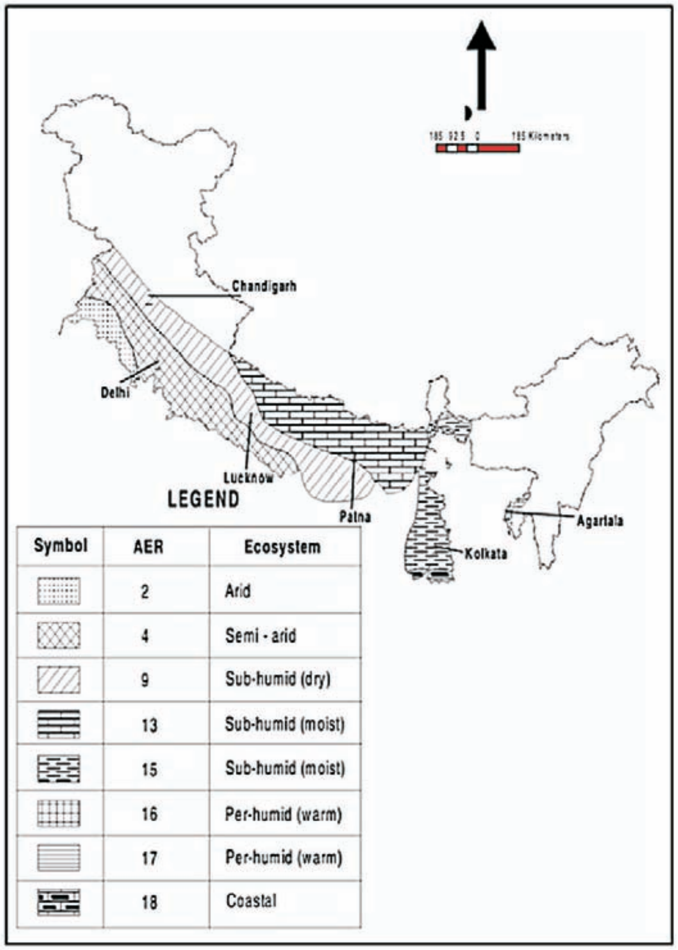
Introduction

The Indo-Gangetic Plains (IGP) ranks as one of the most extensive fluvial plains of the world. The deposit of this tract represents the last chapter of earth's history. The IGP developed mainly by the alluvium of the Indus, Yamuna, Ganga, Ramganga, Ghagra, Rapti, Gandak, Bhagirathi, Silai, Damodar, Ajay, and Kosi rivers. The nature and properties of the alluvium vary in texture from sandy to clayey, calcareous to non-calcareous and acidic to alkaline. Though the overall topographic situation remains fairly uniform with elevations of 150 m in the Bengal basin, and 300 m in the Punjab plain, local geomorphic variations are significant (Shankarnarayana 1982). Geophysical surveys and deep drilling by the Oil and Natural Gas Commission of India suggest that the IGP is a vast asymmetric trough with maximum thickness of 10,000 m that thins out to the south (Sastri et al. 1971; Raiverman et al. 1983). During the past five decades several workers have indicated the various soil-forming processes in soils of the IGP, such as calcification, leaching, lessivage, salinization and alkalinization, gleization, and homogenization (Shankarnarayana and Sarma 1982). The temperature regime is hyperthermic (i.e. mean annual temperature is >22°C and the difference of mean summer and winter temperature is >6°C), but differences in precipitation have contributed to the formation of a variety of soils in the plains that represent mainly three soil orders like Entisols, Inceptisols, and Alfisols. Recent studies indicate that the IGP is dominated by Entisols, Inceptisols, Alfisols, Mollisols, and Aridisols (Bhattacharyya 2004).

The IGP covers about 43.7 m ha area, which is approximately 13% of the total geographical area of India, and produces nearly 50% of the country's foodgrains to feed 40% of the total population of the country. It represents eight agro-ecological regions (AERs) and 14 agro-ecological subregions (AESRs; Fig. 1). The Mughal statistics confirm that much of the land in the IGP was under cultivation. This involved traditional mixed cropping methods. This land-use pattern continued till the middle of the 19th century. Over the last three–four decades the states of the IGP have been successful in increasing their food grain production, chiefly rice and wheat, by introducing high-input technologies to meet the demands of the exponentially growing population. The soils under arid climates require addition of organic matter and phosphorus but not potassium in the initial years of cultivation (Velayutham et al. 2002). The strategies and measures adopted to achieve this success included, among others, (i) the spread of high-yielding varieties, (ii) expansion of irrigated area, (iii) increased use of fertilizers, (iv) plant protection chemicals, (v) strengthening of marketing infrastructure, and (vi) introduction of subsidies. The production of grains is, however, not uniform across the IGP regions because of the spatial variation in land-resource characteristics and socio-economy in the region. Also, these management interventions for 'money economy' have resulted in (i) widespread degradation, (ii) depletion of natural resources, (iii) declining water level, (iv) loss in soil fertility, (v) nutrient imbalance/deficiency, (vi) drainage congestion, and (vii) loss in soil carbon (Abrol and Gupta 1998; Bhandari et al. 2002).

Fig. 1 Location map of the Indo-Gangetic plains (IGP), India showing agro-ecological sub regions



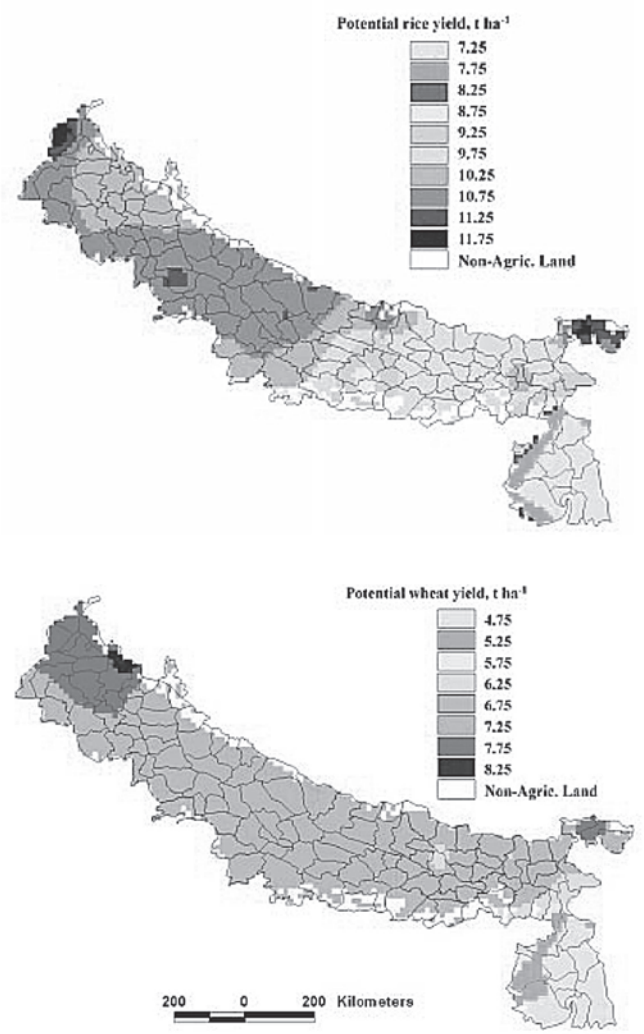
Symbol	AER	Ecosystem
░	2	Arid
▩	4	Semi - arid
▨	9	Sub-humid (dry)
▤	13	Sub-humid (moist)
▤	15	Sub-humid (moist)
▦	16	Per-humid (warm)
▤	17	Per-humid (warm)
▤	18	Coastal

This paper reviews the trends in crop productivity vis-à-vis potential yields, partial factor productivity, and soil fertility in the dominant rice-wheat cropping system of the IGP. The paper also reviews the available information on how efficient nutrient management strategies can increase crop productivity, add to farmer's income, and improve overall agricultural sustainability.

Rice-wheat yields vis-à-vis potential yields

In most parts of the Indo-Gangetic plains of India where rice-wheat is currently produced, climatic factors allow a potential yield between 12.0 and 19.5 t ha^{-1} (Aggarwal et al. 2000; Fig. 2).

Fig. 2 Potential yields (t ha^{-1}) of rice (above) and wheat (below) in the Indo-Gangetic plains of India.



However, average yields of rice + wheat in the Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal currently are 7.5, 6.1, 4.5, 3.3 and 4.4 t ha^{-1}, respectively (Ladha et al. 2003; Table 1). Many farmers in north-west India now harvest almost 16 t ha^{-1} from the rice-wheat system, which indicates negligible yield gaps with the current genetic technology. These yields on per day as well as annual basis are comparable to the best in world considering the level of inputs used. Research for such farmers or regions must now focus on increasing potential yield and input use efficiency. Their study also showed that the yield potential is higher in the northwestern regions compared to the eastern regions and is related to temperatures and solar radiation during crop season. These results are based on the mean weather data. Therefore, small deviations in these estimates are possible at some locations due to climatic variability. These estimates can be used to calculate the magnitude of current yield gap in different regions and the possibility of bridging them to increase food production.

Table 1 Wheat and rice yields under favourable and less favourable rice-wheat systems in India.

State	Wheat yields (t ha^{-1})			% of wheat area under Irrigation 1994-95	Rice yields (t ha^{-1})			% of rice area under Irrigation
	1990-93[a]		1996-97[b] (overall)		1990-93[c]		1996-97 (overall)	
	W-R (fav)[d]	W-R (unfav)			W-R (fav)	W-R (unfav)		
Punjab	3.69		4.24	96.7	4.84		5.10	99.1
Haryana	3.57		3.88	98.4	4.29		4.45	99.6
Uttar Pradesh	2.28	2.03	2.66	92.2	3.04	2.45	3.18	60.4
Bihar	1.79	1.71	2.17	87.8	2.29	1.58	2.14	39.8
West Bengal		2.00	2.39	72.5		2.68	3.27	24.6
Madhya Pradesh		1.04	1.76	67.3		1.20	1.75	23.1

[a] Center for Monitoring Indian Economy. India's Agricultural Sector, July, 1996.
[b] Department of Economics and Statistics, Ministry of Agriculture, India. 1998. Agricultural Statistics at a glance.
[c] Huke and Huke (1997) adjusted to an unhusked rice basis.
[d] Fav = favorable, unfav = unfavorable.

The variation in average yields across different states in IGP indicates that at the regional level there still exist considerable yield gaps in most parts of the plains (Shukla et al. 2004). In Uttar Pradesh and Bihar, there is a large untapped potential for rice and wheat production. For example, Aggarwal et al. (2000) showed that several districts of Uttar Pradesh had potential yields similar to Punjab and Haryana. Yet in most cases farmers of this region were not able to attain higher yields because of sub-optimal input use and land degradation status. Greater focus on nutrient management in these regions in future will help sustain food security of the country for a long time.

Thus, there is a need to determine optimal food production opportunities considering the potential yields, land degradation status as well as socio-economic status of the farmers in a region. The systems approach with its well-developed analytical framework, databases and powerful simulation models can greatly assist us in this endeavour.

Trends in Partial Factor Productivity

Partial Factor Productivity (PFP) is the average productivity, and measured by grain output divided by quantities of fertilizer. This is relatively easy to measure, but its interpretation is not clear. Some workers have calculated trends in the partial factor productivity of fertilizer (PFP-F) over time. Invariably, these calculations show sharply declining trends, and they are cited as a cause for concern. Long-term trends in PFP-F are highly misleading as indicators of sustainability, however, because most of the decline in PFP-F is due to movement along a fertilizer response function, as opposed to a downward shift of the response function itself. The former is not a cause for concern, as it is merely a reflection of the fact that farmers took some time to learn about optimal levels of fertilizer usage. For example, survey data for a group of farmers in Central Luzon in the Philippines show that it took 10 to 15 years after the introduction of modern varieties for average N use in the wet season to increase from 10 to 60 kg ha^{-1} (Ladha et al. 2000). And the spread of higher levels of fertilizer use from one area to another has also taken time, requiring the transmission of knowledge and the construction of irrigation systems. Thus, as modern varieties spread and farmers learned about fertilizer, fertilizer use increased sharply. Since nitrogen response functions are highly concave, this large increase in fertilizer use has led to a sharp decline in the PFP-F. But this decline in the PFP-F is of no concern and does not imply a lack of sustainability in the system.

It, therefore, is highly preferable to calculate trends in Total Factor Productivity (TFP) or use production functions to assess sustainability. The data with which to measure TFP at the farm level are difficult to collect because they require a large amount of detail, including the prices and quantities of all inputs and outputs. Nevertheless, two recent studies by Ali and Byerlee (2000) and Murgai (2000) have estimated trends in TFP in the rice-wheat systems of Pakistan and India, respectively. Ali and Byerlee (2000) calculated TFP growth rates on a cropping systems basis in Pakistan's Punjab from 1966 to 1994. They found positive TFP growth of 1.26% per annum for the entire period for all systems considered together. Growth was positive in the wheat-cotton and wheat-mungbean cropping systems, but was negative in the rice-wheat system, especially in the early years of the Green Revolution (1966-74). Perhaps surprisingly, TFP growth in the rice-wheat system was increasing over time, and was +0.88% per year from 1985 to 1994. Relatively rapid TFP growth in this latter period suggests that there is no imminent crisis of sustainability.

Using district-level data from the Indian Punjab, Murgai (2000) found a similar pattern of relatively slow productivity growth in the early years of the Green Revolution. She argues that this pattern occurs because the technical change induced by the Green Revolution was not Hicksneutral, that is, it favored increased use of certain inputs relatively more than others. Under such conditions, estimates of TFP growth are biased indicators of technological progress. She found that TFP growth from 1985 to 1993 was greater than 1.5% per annum in eight of nine districts in Punjab and Haryana. The only exception was in Ferozepur, where wheat-cotton is the dominant cropping system. According to Murgai (2000), the evidence in India's Punjab “suggest(s) that fears about unchecked reductions in productivity growth are exaggerated.”

It is important to remember that TFP does not directly measure environmental degradation. In fact, Ali and Byerlee (2000) found substantial deterioration of soil and water quality in all cropping systems in Pakistan's Punjab, including those with positive TFP growth. It was most severe in the wheat-rice system, where it reduced TFP growth by 0.44% per annum during the period 1971-94. If TFP growth is positive in the presence of environmental degradation, this indicates that technological progress and improved infrastructure have more than compensated for the environmental degradation. Even if this has happened in the past, however, this is no guarantee that it will continue in the future.

Trends in soil fertility

Research conducted by the International Plant Nutrition Institute (IPNI) in the IGP over the last 20 years indicates a gradual but continuous nutrient mining from soils. Early on in the IPNI program the focus was on the balance between N:P:K, which was highlighted in a couple of publications focused on P and K in particular (Tiwari 2001; Hasan 2002). Most obvious in these early years was the widening ratio of N:P:K in the use of fertilizers, especially after the wide spread nature of P and K deficiencies had been identified. Work with balancing P and K fertilisers resulted in significant yield increases in many trials with multiple crops. In addition, the use of K in many areas of India, increased yield potential and the deficiency of other secondary and micronutrients in crops. This is a characteristic response, which we have observed in countries around the world, where N and P use forms the basis of crop fertilization. Introduction of K results in moderate to significant yield increases, along with quality improvement in crops. However, it also results in deficiencies of secondary and micronutrients becoming obvious in field grown crops. In most of these instances, it is K, which is the most limiting nutrient, and once corrected, it opens the door to further deficiencies in the cropping system (Tandon 1997).

Efficient nutrient management strategies or approaches, and their impact on crop productivity and soil fertility

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 the IGP. Research on farmers' fields has revealed that there is no compelling evidence of significant increases in fertilizer N efficiency in the rice-wheat system during the past 30 years (Dobermann and Cassman 2002). The average plant recovery efficiency of fertilizer N is still only about 30% (Dobermann 2000). 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.

Recent research conducted in various countries including India (Dobermann *et al.* 2002) has demonstrated limitations of the blanket fertilizer recommendations practiced across Asia. Cassman et al. (1996) observed that indigenous N supply of soils was variable among fields and seasons, and was not related to soil organic matter content. On-farm research has clearly demonstrated the existence of large field variability in terms of soil nutrient supply, nutrient use efficiency and crop responses. Thus, it was hypothesized that future gains in productivity and input use efficiency will require soil and crop management technologies that are knowledge-intensive and are tailored to specific characteristics of individual farms or fields to manage the variability that exists between and within them (Tiwari 2007).

Three different nutrient management strategies for efficient nutrient management are being applied today to mitigate the poor soil health in the IGP. One is the soil-test based approach, the second is the plant-based approach, and the third is the satellite imagery technique. In many of the field trials that IPNI has conducted over the years in IGP, fertilizer rates were established based on the concept of crop removal, with an adjustment for soil residual nutrients. While this approach actually fits most production systems in India quite well, given that most of the crop biomass is removed from harvested fields, the role that residual soil nutrients play in meeting crop nutrient requirements becomes a challenge. If a soil tests medium or low in most of the plant nutrients, then application of these nutrients based on target yield crop removal is going to address these nutrient demands. However, on soils where the soil nutrient analysis indicates a high level of nutrient supply the issue of whether to apply the nutrient at removal rates becomes a challenge to the researcher. The issue is one of balanced nutrition for the crop. Addition of high rates of N, P, and K as part of the treatment actually stimulates a deficiency of a secondary or micro-nutrient, which according to soil testing was considered adequate. The best example of this is found with K use in many production systems where soil testing shows that K levels should be more than adequate to meet crop demand, but at what yield level? Many of the recommendations, and soil test levels, used for K guidelines are associated with much lower yields than are currently being targeted by growers. Research conducted by IPNI in India clearly shows that many of these guidelines are inadequate for current yield targets, and as a result a soil test K level once considered adequate turns out to be insufficient to balance the high rates of N and P being applied (Tiwari 2005). As a result, the best option is to apply all macro and secondary nutrients, which are required to meet crop yield removal, and those micronutrients which soil testing show to be marginal or deficient. This then provides the environment for full yield expression in the absence of any nutrient deficiency. And once this yield potential of a site has been determined, the next step is to refine nutrient application rates with further field trials. The impact of secondary and micronutrients was clearly shown in a report of research series of experiments conducted by IPNI on site-specific nutrient management (SSNM) in rice-rice and rice-wheat cropping systems in seven different locations in the IGP. We identified yield-limiting nutrients at each location, and when these nutrients were applied, crop productivity and farmers' profits increased when compared with state-recommended and farmer practices (Table 2).

Table 2 Effect of site-specific nutrient management (SSNM) on wheat productivity (t ha^{-1}) and economic returns (Rs ha^{-1}, in parenthesis) at seven locations in India

Site	FP[a]	SR[b]	SSNM	Increase over SR [% (Rs ha^{-1})]	Increase over FP [% (Rs ha^{-1})]
Ranchi	2.56 (1575)	4.15 (25,276)	4.06 (26,854)	10.0 (1,578)	58.5 (25,309)
Modipuram	4.77 (29,292)	4.90 (31,859)	6.43 (58,083)	31.0 (26,224)	46.5 (28,791)
Kanpur	4.72 (7,258)	5.45 (17,644)	6.00 (31,338)	10.1 (13,694)	27.1 (24,080)
Ludhiana	5.45 (27,772)	6.28 (39,105)	6.55 (46,219)	4.3 (7,114)	20.1 (18,447)
Sabour	3.92 (18,306)	4.97 (28,614)	5.82 (45,116)	17.1 (16,502)	48.7 (26,810)
Pantnagar	3.87 (7,828)	5.10 (14,276)	6.39 (19,426)	25.3 (5,150)	66.0 (11,598)
Palampur	2.64 (55,122)	3.76 (54,583)	3.87 (60,905)	3.0 (6,322)	46.5 (5.783)

[a] FP= Farmers' practice

[b] SR= State fertilizer recommendation

The plant-based SSNM approach was evaluated comprehensively for agronomic, economic, and environmental performance in 56 farmers' fields with irrigated wheat and transplanted rice in Punjab (Khurana *et al.*, 2007; Khurana *et al.*, 2008). The results of the study clearly brought out the positive impact of SSNM on grain yields, and agronomic recovery, and physiological efficiencies of N under rice-wheat cropping system in Punjab vis-à-vis farmer's practice. Also, the highly negative P and K balances observed in farmers' fields were reduced using the SSNM approach indicating that SSNM promotes more balanced fertilization than is followed by farmers.

Very recently, IPNI has successfully tried the Geographical Information Systems (GIS) mapping approach to measure the spatial variability in nutrient status (Sen *et al.*, 2007) and used such maps as a site-specific fertilizer recommendation tool to positively impact rice yields in farmers' fields (Sen *et al.*, 2008). This mapping is based on two factors: (a) nutrient content of agricultural soils varies spatially due to variation in genesis, topography, cropping history, fertilization history, and resource availability and (b) soil testing of all holdings to estimate native fertility levels to ensure appropriate recommendation is a logical step, but we do not have adequate infrastructure to accomplish this task. The process of soil fertility mapping involved geo-referenced soil sampling and using the soil analysis data in a GIS platform to develop surface maps of analyzed soil parameters across the study area. The spatial variability maps created by combining the location information of the sampling points (latitude/longitude) and the analyzed soil parameter are capable of predicting soil parameter values of un-sampled points. This is possible because the interpolation technique used in the GIS platform creates a smooth surface map of the study area utilizing point information (geographic location and corresponding soil parameters), where each point on the map has a soil parameter value associated with it. The possibility of using such maps as a fertilizer decision support tool to guide nutrient application in a site-specific mode is being explored in several studies under IPNI research initiative. Besides, delineating the fertility management zones within the study area, these maps can give a clear visual indication of the changing fertility scenario at a village level with time, which is important for nutrient management planning (Sen et al., 2008). Besides the logistical and economic advantages of implementing such a system, once established, the technique can create an effective extension tool where field agents work more directly with farmers. Thus, farmers become more aware of how their fields rank within the landscape in terms of basic soil fertility, which in turn enables a system of more rational use of fertilizer application. These tools are far from perfect, but they do help to overcome many of the challenges associated with state wise recommendations.

Conclusions

Crop productivity, factor productivity, and soil fertility are not uniform across the IGP regions because of the spatial variation in land-resource characteristics and socio-economy in the region. Also, the imbalanced fertilizer application in the IGP has resulted in stagnating or declining yields, nutrient use efficiencies, and soil health. To improve the situation, new and more efficient, knowledge-intensive, and site-specific strategies of nutrient management need to be adapted and applied.

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Evaluation of soil fertility and nutrient balances under intensive agriculture

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Abstract The food grain production in India, which was only 82 million tonnes (mt) during 1960-61 before the green revolution period increased to 230 mt in 2007-08. The large increase in food grain production has resulted from the increase in productivity with increased use of fertilizer, irrigation water, adoption of new technology and increased intensity of cropping. The fertilizer consumption has increased from 70,000 t in 1951-52 to about 23 mt in 2007-08. However, the partial factor productivity (for fertilizer NPK) for food grain production has declined from 48 in 1970-71 to 10 in 2007-08. A large part of this decrease could be ascribed to gradual decline in the indigenous supply of soil nutrients leading to macro- and micronutrient deficiencies due to inappropriate fertilizer application and little recycling of organic sources. A number of fertilizer recommendation strategies have been developed, each of which has its own merits and limitations under different soil, crop and climatic conditions. While there is wide scale adoption of blanket fertilizer recommendation and to a lesser extent of soil-test based fertilizer adjustments, there is a need for site-specific nutrient management for balanced fertilization. There is a need to monitor soil fertility and emerging nutrient deficiencies and to adopt appropriate practices for alleviation. Soil test methods for fertility evaluation and for formulating fertilizer recommendations must be augmented with other chemical and biological fractions to achieve higher fertilizer use efficiency (FUE).

Keywords Soil testing • fertilizer use efficiency • balanced fertilization • nutrient mining • soil test interpretation

Introduction

In India, the growth in food grain production during the last four decades, which has been associated with the well known "Green Revolution", saw the development and adoption of new high yielding varieties of wheat, rice and other

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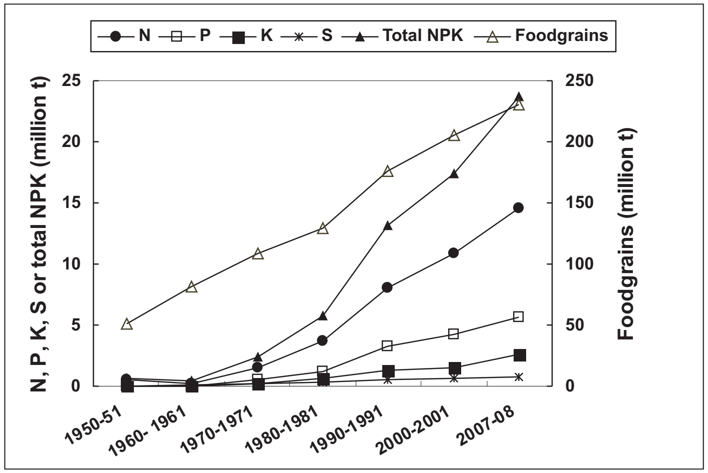
food crops responsive to fertilizer nutrients. The food grain production, which was only 82 million tonnes (mt) during 1960/61 before the green revolution period increased to 130 mt in 1980-81 and 230 mt in 2007-08. The large increase in food grain production during the last four decades has resulted from the increase in productivity with increased use of fertilizer inputs, irrigation water, adoption of new technology and increased intensity of cropping. Of India's gross cropped area of 191 m ha, net sown area of 141 m ha has remained nearly constant over the last 40 years. Cropping intensity showed an increase of 70% over last 60 years but more than 3-fold higher rate of population increase led to steep decline in per capita gross sown area availability from 0.36 to 0.16 ha per person. The fertilizer consumption has increased by more than 328 times since 1951-52. The dramatic increase in fertilizer consumption and increase in agricultural productivity is an indication of the critical role of fertilizers. It is imperative that fertilizers are used in a judicious manner for maximizing their use efficiency and crop productivity. Any inefficient use of fertilizers is liable to make fertilizer consumption uneconomical and unecological that can cause environmental pollution and groundwater contamination. Formulation and adoption of careful strategies for applying appropriate amount of nutrients at proper time using right methods would help to increase fertilizer use efficiency (FUE) and reduce soil, water and air pollution.

A number of fertilizer recommendation strategies have been developed and used for making fertilizer recommendations to the farmers. Each of these has its own merits and limitation under different soil, crop and climatic conditions. In this paper, we i) summarize the trends in fertilizer use and response to their application, ii) synthesize information on soil fertility evaluation approaches and fertilizer recommendation philosophies, and iii) critically evaluate the impact of nutrient management strategies on nutrient balances, crop productivity and nutrient use efficiency.

Trends in fertilizer use and declining crop response to fertilizer application

India is second only to China in fertilizer N and P consumption. The fertilizer consumption during 2007-2008 was 23.01 mt comprising 14.63 mt N, 5.72 mt P_2O_5 and 2.66 mt K_2O. During the last 60 years there has been tremendous increase in fertilizer consumption in India. The fertilizer consumption has increased from 70,000 t in 1951-52 to about 23 mt in 2007-08 (Fig. 1). However, there is still a net negative balance of 10 mt (36%) between NPK removal and application. This is a serious soil health hazard, which needs urgent attention of all concerned. With country's overall average consumption of 119 kg NPK ha^{-1} year^{-1}, the variations among different regions are tremendous as some areas receive adequate (or even excessive) fertilizers and others are severely deficient. The intensity of fertilizer application in different regions appears to be guided by the availability of irrigation water.

Fig. 1 Trends in fertilizer N, P, K and S consumption and food grains production in India during 1950-51 to 2007-08 (FAI 2007, 2008)



It is not only the consumption of fertilizer nutrients but also the nutrient use efficiency that is important from biophysical and economic point of view. Trends over the last 40 years show that the productivity of food grain crops, particularly rice and wheat is stagnating and the crop production system is no longer exhibiting increased production with increase in input use. The partial factor productivity (for fertilizer NPK) for food grain production in India has gradually declined from 48 in 1970-71 to 10 in 2007-08 (Fig. 2).

The scenario is similar for high fertilizer consuming state of Punjab where the partial factor productivity of NPK has dropped from a high of 80.9 in 1966-67 to 14.9 in 2006-07 (Benbi et al. 2006). This shows that the nutrient use efficiency of the added fertilizers is dropping; so the framers must add increasing amounts in order to merely maintain yields. Evidence of declining partial or total factor productivity has also emerged from long-term experiments. Thirty-years trends (1972-2003) of response ratios (kg grain/kg nutrient) averaged for several crops and locations [rice (Barrackpore), wheat (Barrockpore, Ludhiana, Pantnagar and Palampur), maize (Ludhiana and Bangalore) and finger millet (Bangalore)] showed that with the imbalanced application of nutrients the response ratio declined with time (Fig. 3). With the balanced application of NPK the response ratio over the years remained unaltered. The response ratios showed a rising trend only when chemical fertilizers were supplemented with organic manure.

Fig. 2 Partial factor productivity of fertilizer NPK for food grains production in India during the years 1960-61 to 2007-08. (FAI 2007, 2008)

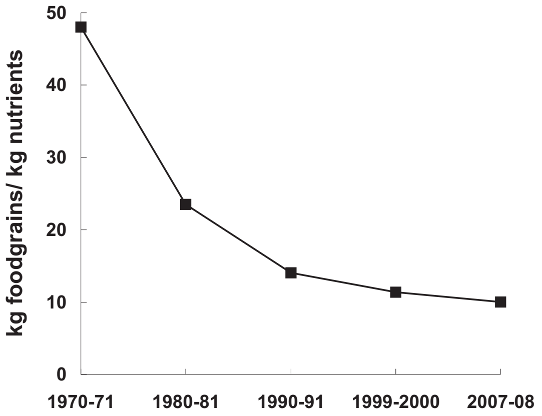
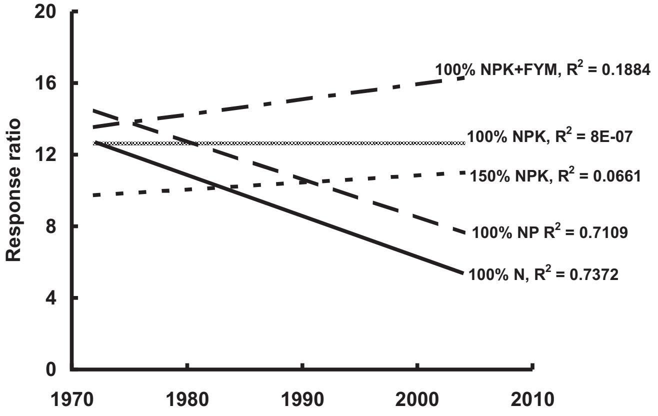
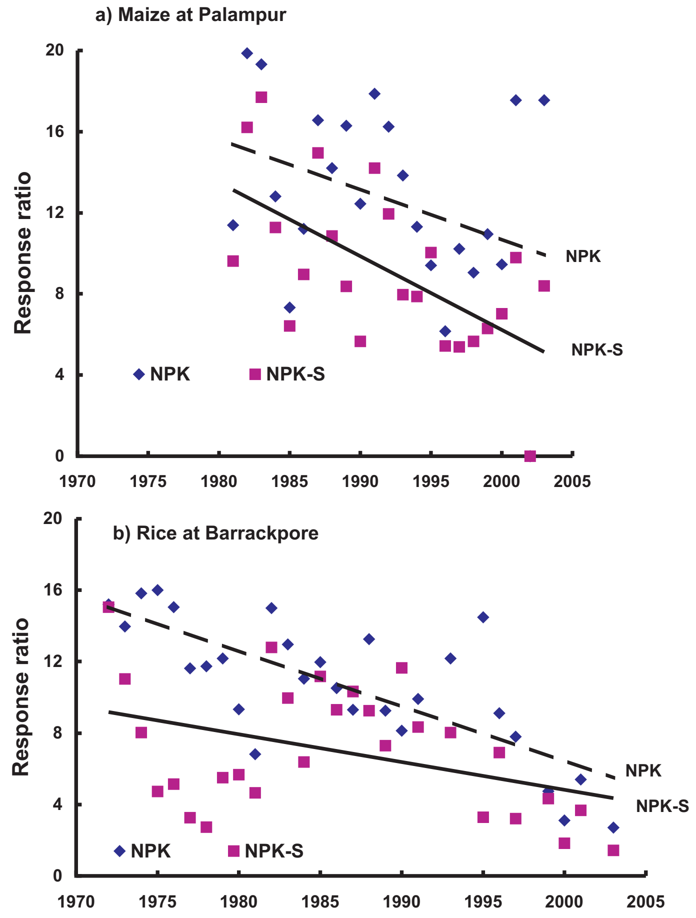


Fig. 3 Nutrient response ratios (kg grain kg^{-1} nutrient) in cereals. Drawn from long-term fertilizer experiments data averaged over 1972-2003 and several locations of rice, wheat, maize and finger millet (Samra 2006)



There could be many reasons for the decline in the crop responses to applied fertilizer nutrients. First, it is natural, since the law of diminishing returns will operate and show its effect with each successive increase in fertilizer nutrient dose. But a large part of this decrease could also be ascribed to gradual decline in the indigenous supply of soil nutrients leading to macro- and micronutrient imbalances due to inappropriate fertilizer application and little recycling of organic sources. However, results of a recent study showed that with balanced and adequate application of fertilizer nutrients there is no decline in soil fertility (Benbi and Brar 2009). The results from long-term fertilizer experiments show that when S application was omitted from fertilization schedule, the deficiency of S and the drop in the response ratios became evident in maize and rice at different sites in India (Fig. 4). Similarly, the omission of Zn from the fertilization schedule led to lowering of average response ratios of crops at different locations. These observations emphasize the need to monitor soil fertility status and emerging nutrient deficiencies and to adopt appropriate management practices for improved nutrient use efficiency.

Fig. 4 Response ratio (kg grain kg^{-1} nutrient) of sulphur in a) maize at Palampur and b) Rice at Barrackpore. Data from long-term fertilizer experiments (Samra 2006)



Soil fertility evaluation

A proper evaluation of the fertility of a soil is the key to achieve efficient fertilizer use and take appropriate measures to alleviate constraints to productivity. Soil testing and plant analysis are useful tools for soil fertility evaluation and for devising nutrient management practices.

Soil testing

The aim of soil testing is to estimate the nutrient–supplying power of a soil. The methods for evaluating the soil fertility may be biological or chemical. Since the biological methods are time consuming and do not fit into routine batch process of the soil testing laboratories, chemical methods are generally followed. The chemical methods for evaluating the soil fertility involve analyzing a soil sample for plant available fraction of an essential plant nutrient(s), which is(are) expected to be in relatively short supply and whose deficiency can be corrected by appropriate additions of suitable fertilizer. The choice of a chemical method to estimate nutrient availability in soils is based on the relationship between crop yield or crop response and the soil test values. There is always some theoretical basis for the choice of a method. Soil test results are used to classify soils into low, medium and high categories. Such a classification is based on soil test crop response relationship studies. Obviously, application of a nutrient in a soil testing low in that particular nutrient will result in greater increase in crop yield as compared to a soil testing medium in its nutrient supplying capacity.

Plant analysis for diagnosing nutrient deficiencies

Although plant analysis is not a direct evaluation of soil fertility, yet it is a valuable supplement to soil testing. Plant analysis is useful in confirming nutrient deficiencies, toxicities or imbalances, identifying hidden hunger, and determining the availability of nutrients. Plant analysis can be particularly useful in determining the bio-availability of nutrients in situations when adequate level of a nutrient may be present in the soil, but its availability is constrained due to problems such as soil moisture conditions and inadequate amounts of other nutrients. Plant analysis includes: (i) Tissue tests made on fresh tissue in the field, and (ii) the complete chemical analyses conducted in the laboratory. Rapid tests, generally conducted for N, P and K, on the sap from ruptured cells, are semi-quantitative and predict nutrient deficiencies on the spot. For most diagnostic purposes, plant analyses are interpreted on the basis of critical value approach that uses tissue nutrient concentration calibrated to coincide with 90 or 95% of the maximum yield; below this value the plants are considered deficient and above that value sufficient (Munson and Nelson 1990). For example, S content in plant foliage during active growth is a quite good parameter to ascertain S sufficiency. Several studies have revealed that the S content below 0.2% in the plant tissue at the pre-flowering stage of *Brassica* was the threshold level, below which the crop yield and quality were adversely affected (Aulakh 2003). For most crops, there is a sufficiency range of nutrient composition over which yield will be maximized rather than a single value.

The major disadvantage of critical value and sufficiency range approach is that it does not consider nutrient balances and interactions and require different critical values for different tissue ages. Nutrient ratios are considered as a better tool as it takes care of nutrient interrelationships. To further enhance the reliability of plant analysis, the Diagnosis and Recommendation Integrated System (DRIS), which considers nutrient concentration ratios, rather than individual elemental concentration, has been proposed (Walworth and Sumner 1987). The DRIS approach measures the relative balance between nutrients by means of index values with negative values indicating insufficiencies and vice versa. The DRIS approach can also be employed to compute low, sufficient, high, and excessive/toxic ranges for nutrients (Bhargava 2002). This approach has been used for diagnosing nutrient requirement of several fruit plants (Hundal and Arora 1995 and 2001; Hundal et al. 2007) in Indian Punjab, but the results have neither been validated nor used for advisory purposes.

Soil test interpretation and fertilizer recommendations

Several approaches have been used to formulate nutrient management practices for different crops. These include (i) Generalized fertilizer recommendations (GRD), (ii) Soil test based fertilizer recommendations (STRD), (iii) Critical value or sufficiency approach, (iv) Build-up and maintenance concept, v) Fertilizer recommendations for targeted yield of crops or site-specific fertilizer recommendations (vi) Building and maintenance concept, (vii) basic cation saturation ratios, and (viii) Response surfaces and mechanistic modelling. Both the sufficiency range of available nutrients and basic cation saturation concepts recognise that a fraction of a plant nutrient measured by soil tests is available to plants and its level may range from low to high. The sufficiency approach is based on law of diminishing returns where increase in crop yield per unit of available nutrient decreases as the level of available nutrient approaches sufficiency. The concept of basic cation ratios is based on the premise that for most crops there is a best ratio of basic cations on the soil cation exchange capacity. Any given concept seems to work well under specific conditions. Out of these concepts, the following approaches for formulating fertilizer recommendations are most commonly used.

Generalized fertilizer recommendations

Generalized or state level blanket fertilizer recommendations (GRD) are most commonly advocated and followed. Although it is based on the findings of field experiments conducted across a state or a region, it does not take care of several variants determining FUE. Generalized recommendations are ideally suited for soils of medium fertility. Obviously, due to variation in soil fertility uniform adoption of GRD does not ensure economy and efficiency in fertilizer use. It leads to the wastage of fertilizer in high fertility and suboptimal usage in low fertility soils. This is particularly so as majority of soils in India are low (63%) in available N and high (50%) in available K (Motsara 2002).

Soil-test based fertilizer recommendations

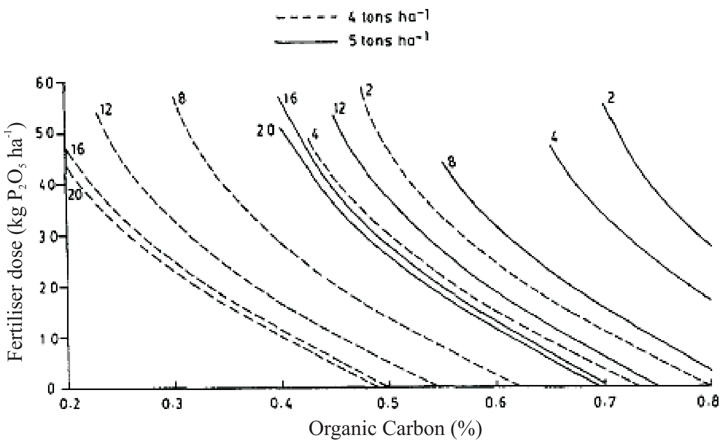
The soil-test based fertilizer recommendations (STRD) are based on classification of soils into low medium and high categories based on soil test values for plant available N, P and K. The fertilizer dose is increased by 25% over the GRD if soil is testing low and decreased by 25% if soil is testing high. However, this approach suffers from the limitation that it recommends the same fertilizer dose for extremely deficient and marginally deficient soils. Similarly, soils having extremely high and moderately high status of available nutrients receive the same set of fertilizer recommendations. Considerable economy in fertilizer use can be made if actual soil test values, instead of soil fertility classes, are used in formulating fertilizer recommendations.

Another limitation of STRD approach is that the fertilizer recommendations are usually formulated based on the soil fertility class of an individual nutrient but its interactive effect with other nutrient or soil properties is not considered. It has been observed that the availability of a nutrient to plants depends not only on its own concentration in soil but also on other soil properties. For example, Benbi and Brar (1994) showed that the crop response to P application varies with soil P and organic carbon (SOC) status (Fig. 5).

Critical value approach

The critical value approach is used to separate soils that give little or no response from those giving high response to applied nutrients. Data collected systematically to calibrate soil tests with crop response to applied nutrients provide a suitable basis to define critical values. Cate and Nelson (1965; 1971) suggested the use of a graphical and a statistical method to accurately estimate critical value from soil test crop response data. In the graphical approach, the yields of the control as percentage of the maximum yield (percent yield) for different soils are plotted on the Y-axis against the soil test values on the X-axis. A vertical line and an intersecting horizontal line is drawn on the graph paper in such a manner that the number of points in the first and the third quadrants are the maximum and the numbers in the second and fourth quadrants are the minimum. This placement ensures that bulk of the points are concentrated in two quadrants: one in which low soil test values are associated with low relative yields and the other in which high soil test values are associated with high relative yields. The statistical approach is based on the hypothesis that responsive soils and non-responsive soils are two distinct populations in which relationship between soil test values and relative yields are described by two different straight lines. The procedure involves iteratively separating percentage yield data into two or more classes by maximizing the class sum of squares in a one-way analysis of variance. The sum of squares reflects the weighted sum of squares between the percentage yield means for the various classes and the grand mean. The set that gives the least sum of squares defines the critical value. This method of separating soils into different fertility classes is considered superior to subjective classification into low, medium and high categories. Benbi and Brar (1992) presented another approach for computing minimum response to applied fertilizer, which is likely to be obtained at a particular soil test level. It involves calculation of lower 60 percent confidence limits for relative yield and fitting $\log_e$-linear regression to the transformed data. The approach has been found to hold good on published data by the authors.

Fig. 5 Wheat yield inoculants for 4 and 5 tons grain ha^{-1} in relation to soil organic carbon at different levels of Olsen P. Values at the top of the curves indicate Olsen P (mg kg^{-1}) (Benbi and Brar 1994)



Some information on critical limits of available P and K in well-known soil types of India for different crops are presented in tables 1 and 2, respectively. As is apparent from the tables, the critical value of available nutrient in soil varies with soil type and the crop grown. For example, the critical limit for available ($NaHCO_3$-extractable) P in soil for wheat ranges from 3.3 mg kg^{-1} in alluvial soils to 16.3 mg kg^{-1} in black soils (Table 1).

Table 1 Critical limits of available P in soils for different crops and soils based on data from different regions of India (Adapted from Subba-Rao and Reddy 2006)

Crop	Soil type	Critical limit (mg P kg^{-1} soil)
Rice	Alluvial	10.6-11.8
	Red	2.9-3.5
	Black	5.8-6.5
	Laterite	13.6
Wheat	Alluvial	3.3-7.9
	Black	9.4-16.3
Pearlmillet	Alluvial	4.8
	Black	7.7
Maize	Alluvial	12.3
Groundnut	Black	6.5
	Alluvial	16.6
Raya	Alluvial	5.1-6.5
Cotton	Alluvial	11.9
Sugarcane	Alluvial	4.8
Potato	Alluvial	8.6-11.5

Information compiled from different studies shows that the critical value of available (NH_4OAc-extractable) potassium ranges from 47 mg K kg^{-1} soil for maize in Haplustalfs to 335 mg kg^{-1} soil for sorghum in Vertisols (Table 2). Obviously, the potassium availability depends on the amount of exchangeable K and soil mineralogy. Exchangeable K is generally more in the Vertisols and Vertic type soils and in the fine-textured alluvial soils than in the red and latertic soils, acidic alluvial soils with kaolinite as dominant clay mineral, and coarse-textured alluvial soils. Most alluvial soils have illite as the dominant mineral in their clay fraction and quartz- feldsapr, quartz-mica or quartz alone as the dominant mineral in their silt fraction. All black soils have smectite as the dominant clay mineral while quartz alone is the dominant mineral in the silt fraction in several soils and feldspar in others. All red, laterite and acid-sulphate soils have kaolinite as the dominant clay mineral and generally quartz as the dominant mineral in the silt fraction. Because of appreciable contribution of non-exchangeable K towards soil K supply it is relatively difficult to establish critical limits for available potassium in soils. Studies on soil test calibration based on non-exchangeable K are limited. Categorization of soils based on non-exchangeable K can be used as a measure of their relative K supplying capacity to soil.

Table 2 Critical limits of available K (NH_4OAc extractable) in soils for different crops based on data from different regions of India (Adapted from Subba-Rao and Reddy 2006)

Crop	Soil	Critical limit (mg K kg^{-1} soil)
Rice	Medium black	100
	Red soils	75
	Alluvial	190
	Calcareous	58
	Laterite	76-87
Wheat	Calcareous	60
	Alluvial	95-100
Maize	Calcareous	81
	Haplustalfs	47
Sorghum	Typic Chromusterts	335
Pearl Millet	Alluvial	160
	Medium black	95
	Black calcareous	137
Cotton	Alluvial	50
Groundnut	Black calcareous	65

Site-specific nutrient management

Site-specific nutrient management (SSNM) is an approach for feeding crops with nutrients as and when needed. The application and management of nutrients are dynamically adjusted to crop needs of the location and season. The SSNM approach aims to increase farmer's profits through increased yield of crops, site and season-specific application of nutrients (primarily N, P and K) and optimal use of existing indigenous nutrient sources such as crop residues and organic manures. In the SSNM approach, advocated by International Rice Research Institute (IRRI), N application to rice is made using leaf colour chart (LCC) or Chlorophyll meter. Nutrient omission plot technique is used to determine the soil supply of P and K (Dobermann et al. 2002).

Another approach involving site–specific nutrient management, known as “target yield concept”, is being advocated in India since late 1960s (Ramamoorthy et al. 1967). The approach is unique in the sense that it not only prescribes the optimum dose of nutrient based on soil fertility status but also predicts the level of yield that a farmer can expect. The targets can be chosen based on farmer's resources. Considering the crop yield to be a continuous function of plant nutrient supply in the growth medium, calibrations are obtained for different levels of soil fertility (created in adjacent field plots with addition of different amounts of fertilizers to the preceding crop, in the cropping sequence) with a given crop in a soil. The procedure of creating different levels of fertility artificially in adjacent plots is adopted to ensure homogeneity in soil management and weather, whose diversity in experiments performed at different locations and in different seasons usually leads to poor correlations. From such experiments, fertilizer dose to attain a specified yield target is obtained [Equation 4] by computing three basic parameters, namely (i) NR- nutrient requirement per unit of economic yield, [Equation 1] (ii) CS- contribution from soil available pool [Equation 2] and (iii) CF- fractional recovery of applied fertilizer nutrient [Equation 3].

$$\text{NR (kg nutrient / Mg grain)} = X_f / GY \qquad (1)$$

$$\text{CS} = X_0 / STV_0 \qquad (2)$$

$$\text{CF} = (X_f - (STV_f \times CS))/A_f \qquad (3)$$

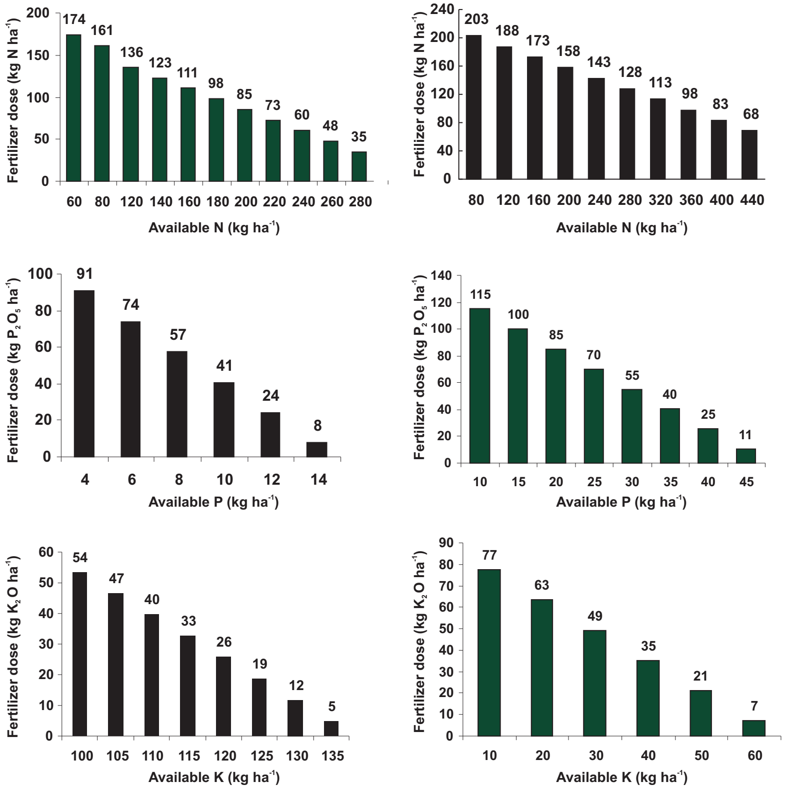
$$\text{Fertilizer dose (kg ha}^{-1}\text{)} = \frac{(NR*T) - (CS \times STV)}{CF} \qquad (4)$$

Where X_f and X_0 represent amount (in kg) of nutrient in the grain and straw of fertilized and unfertilized crop, respectively; GY is the grain yield (in megagram, Mg), STV represents soil test value (in kg ha^{-1}) with subscripts *f* and *0* indicating soil test value of fertilized and unfertilized plots, respectively; A_f is the amount of fertilizer nutrient applied (in kg ha^{-1}); T is the target grain yield (in Mg ha^{-1}). The approach has also been applied for integrated nutrient management where inorganic fertilizers are applied together with organic sources (Benbi et al. 2007).

Under All India Coordinated Research project on soil test crop response correlation (STCR), fertilizer adjustment equations have been developed for a number of crops in the country (Subba Rao and Srivastava 2001; Muralidharudu et al. 2007). Figure 6 shows the typical soil-test based fertilizer recommendations for targeted yield of rice (7 Mg ha^{-1}) and wheat (5.5 Mg ha^{-1}) grown in alluvial soils of Punjab (Benbi et al. 2007). Obviously, considerable adjustment in fertilizer amount can be made if soil test values are taken into consideration. It results in higher economic benefit and FUE over GRD.

One of the major difficulties with the approach is the precise estimate of contribution of nutrient from soil available pool (CS) (Benbi and Chand 2007). Poor estimate of CS is most often the reason for imprecise calculation of fertilizer dose for a targeted yield. The percent contribution from the soil is influenced by soil type, texture, rooting depth and nutrient release characteristics of the soil.

Fig. 6 Soil test based fertilizer recommendations for targeted yield of rice (7 t ha^{-1}) and wheat (5.5 t ha^{-1}) grown in alluvial soils of Punjab (Benbi et al. 2007)



Since the percent nutrient contribution from soil is obtained by dividing the nutrient uptake in control plots by soil test value (see equation 4), the approach is heavily biased towards high fertility of native and applied nutrients (Milap-Chand et al. 2004). Low CS values, especially at high P soil tests, underestimate P supply and provide exaggerated fertilizer P requirements.

The approach is a step ahead of STRD and critical value approach as fertilizer recommendations to crops are made on the basis of the actual amount of nutrients that are likely to be made available to crops during period of growth. This approach takes into account the nutrient requirements of the crop, nutrient supplying power of the soil and the percent recovery of applied fertilizer nutrients. In essence STCR approach integrates both soil and plant aspects. The approach has been validated in several follow-up experiments at farmer's fields (Muralidharudu et al. 2007).

Imbalanced fertilization and nutrient balances

It has become increasingly clear that crops should receive nutrients in adequate and balanced amounts for sustainable crop productivity, optimum nutrient-use efficiencies, and reduced environmental risks. The present NPK use ratio of 6.8:2.8:1 in India is typically unfavourable to K when compared to the generally proclaimed ideal ratio of 4:2:1. Imbalanced use of NPK, resulting in the mining (NPK removed by crops- NPK applied as fertilizer or manure) of native soil nutrients, is considered to be the main cause for declining crop response ratios. In addition to NPK, soils are also getting depleted of secondary and micronutrients especially sulphur and zinc; about 46 % of the Indian soils are reported to be deficient in these two nutrients. This calls for increased focus on application and management of S and Zn in Indian soils.

Balanced nutrient use does not mean use of N, P and K in a fixed ratio in all situations. Balanced fertilization means having all plant nutrients available to the plants in adequate, but not toxic or imbalanced amounts. The ratio of 4:2:1 could be satisfactory for cereals but for other crops like legumes etc. the ratio could vary from 1:2:1, 1:1:1 to 2:1:2 (Aulakh and Malhi 2004). Balanced nutrient use involves both rate and ratio. For example, recommended rates of 120 kg N, 60 kg P_2O_5 and 30 kg K_2O ha^{-1} for wheat in most of the states in India provide a balanced ratio of 4:2:1. If a farmer applies 80-40-20, the ratio is still 4:2:1, but rate applied is less and hence imbalanced application.

As compared to N and P, the use of K in India is very small (see Fig. 1). But the removal of K by crops is 19 and 150% greater than that of N and P, respectively. Farmers generally do not apply K to cereals and prefer to apply to cash crops. Tandon and Sekhon (1988) found negative K balances in wheat and rice amounting to 61 and 141 kg K_2O ha^{-1}, whereas fertilization of potato yielded a positive balance of 87 kg K_2O ha^{-1}. Negative balance indicates that mining of soil K has progressively increased. Results of K indexing in soils over a period of 10 years (Sekhon 1999) and long-term fertilizer experiments (Brar and Brar 2002) showed a substantial decline in exchangeable and non-exchangeable K with time. The north Indian state of Punjab having highest productivity of wheat (4.52 t ha^{-1}) and paddy (5.80 t ha^{-1}), shows the greatest imbalanced use of NPK (33.7:9.2:1.0) and substantial mining of K from soils. Data compiled by Brar (2004) show that the net negative balance of K in Punjab has increased from 0.159 mt in 1960-61 to 0.806 mt in 1994-95. Because of increase in K consumption during late 1990s, the negative balance slightly declined (0.68 m t) in 2002-03. Data from a long-term fertilizer experiment on maize-wheat cropping system showed that after 13 cycles cropping the exchangeable and non-exchangeable forms of K in soil declined in the fields that did not receive potassium fertilizer. There was substantial release of K from the non-exchangeable form (Table 3).

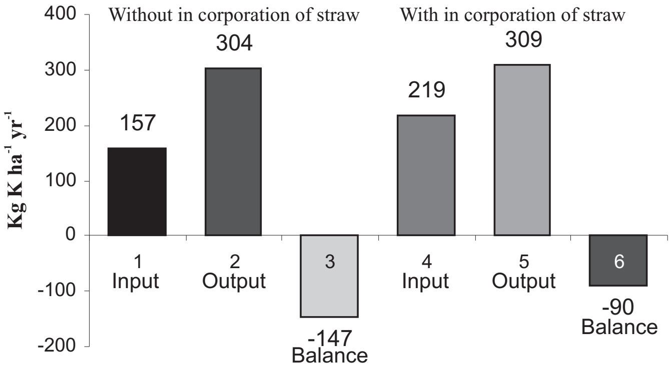
Table 3 Potassium removed by 13 crop cycles (maize-wheat) and its effect on exchangeable- and non-exchangeable K in soils (1970-71 through 1983-84) (Adapted from Singh and Brar 1986)

Treatment	Total K removed (kg ha^{-1}) a	Total K applied (kg ha^{-1}) b	ΔE-K (kg ha^{-1}) c	ΔNE-K (kg ha^{-1}) d	Total E-K + NE- K (kg ha^{-1}) e = c+d	Release from NE - K (kg ha^{-1}) f = a+-c	Unaccounted K (kg ha^{-1}) a-e
Control	803	0	-51	-597	-648	752	155
N_{100}	1392	0	-72	-1110	-1182	1320	210
N_{100} P_{22}	1766	0	-78	-1483	-1561	1689	205
$N_{100}P_{22}K_{41}$	2323	1097	+6	-1101	-1095	1250	149

Δ E K= change in exchangeable K, ΔNE-K= change in non-exchangeable K

In the absence of K application, there was a net negative balance of 136 kg K_2O ha^{-1} yr^{-1} indicating substantial contribution from non-exchangeable forms. Even with the application of 83 kg K_2O ha^{-1} yr^{-1}, the removal of K was 179 kg K_2O ha^{-1} yr^{-1} and about 100 kg K_2O ha^{-1} yr^{-1} was contributed from the soil-reserve sources. After considering total removal of K, amount applied and changes in exchangeable and non-exchangeable forms of K, 149-210 kg K ha^{-1} was unaccounted for, which was contributed by the ground water used for irrigation (Singh and Brar 1986). Similarly, under intensive rice-wheat cropping system receiving 158 kg K_2O ha^{-1} yr^{-1} (50+100+8 kg K_2O ha^{-1} yr^{-1} from fertilizer, irrigation water and rain/seed, respectively) , a net negative K balance of 150 kg K_2O ha^{-1} yr^{-1} has been reported (Fig. 7). Even after considering the contribution of rice and wheat straw incorporation, (= 60 kg K_2O ha^{-1} yr^{-1}), the net negative balance is 90 kg

Fig.7 Annual balance of potassium (kg K ha^{-1} yr^{-1}) in long term rice-wheat cropping system at Ludhiana (India) during 1988 through 2000 (Yadvinder-Singh et al. 2004)



K_2O ha^{-1} yr^{-1} (Yadvinder-Singh et al. 2004). At farmers' fields, the negative K balance could be still higher as the farmers usually do not apply K fertilizers to wheat and rice. Thus the non-exchangeable K will be depleted at a faster rate and will ultimately influence the K-mineralogy of soils.

Imbalanced application of nutrients does not result in realizing potential yields and results in low FUE. This also has environmental implications as low nutrient use efficiencies may lead to the nutrients' accumulation, loss through leaching and gases causing environmental pollution (Aulakh and Malhi 2004). Results of a long-term experiment showed a significant role of balanced application of P and K along with N in reducing NO_3^--N accumulation in the soil profile, which would otherwise be prone to losses through leaching and denitrification (Benbi et al. 1991). Similarly, N removal and apparent N recovery by both maize and wheat was directly related to the balanced application of N, P and K fertilizers. Averaged over 22 years of data, application of N alone resulted in a recovery of 17.1% in maize and 31.7% in wheat. The application of P and K along with N almost doubled (32.8% in maize and 64.7% in wheat) the apparent N recovery in the crops (Benbi and Biswas 1997). However, the improvement in FUE with balanced application of NPK depends on crop, soil type and soil's inherent capacity to supply nutrients. Twenty-nine years mean data for maize-wheat and rice-wheat cropping system at different locations showed highest increase in FUE in maize-wheat sequence in Alfisols at Palampur. Application of N alone yielded a very low recovery efficiency of 6.4% in maize and 1.9% in wheat. Balanced application of NPK improved the N recovery efficiency to 52.6 and 50.6% in maize and wheat, respectively (Table 4).

Phosphorus use efficiency can be enhanced only if no other nutrient is limiting in the soil. Studies have revealed the lowest P use efficiency, when it was applied without adequate dose of N. As observed by Benbi and Biswas (1999), application of N and K along with P further enhanced P use efficiency (Table 5). Similar effects of other deficient elements such as S, Zn, Mn etc. may be expected on P use efficiency.

Table 4 Influence of balanced fertilization on N and P use efficiency in maize-wheat and rice-wheat cropping systems in different soil types (29-year mean). (Singh et al. 2004)

Crop	Soil type/Location	Apparent N recovery (%)			Apparent P recovery (%)	
		N	NP	NPK	NP	NPK
Maize	Inceptisols/Ludhiana	16.7	23.5	36.4	10.3	21.4
Wheat		32.0	50.6	63.1	20.6	30.7
Maize	Alfisols/Palampur	6.4	34.7	52.6	21.8	35.6
Wheat		1.9	35.6	50.6	10.7	15.2
Rice	Mollisols/Pantnagar	37.5	40.7	44.4	18.2	23.3
Wheat		42.4	46.1	48.4	11.2	10.4

Table 5 Influence of rates and balanced N, P and K application on apparent fertilizer P recovery (%) in maize and wheat during 20 years of cropping (Benbi and Biswas 1999)

Treatment	1971-80	1981-90
	Maize	
100% NP	15.7	7.3
100% NPK	29.2	12.7
50% NPK	21.2	10.1
150% NPK	19.9	8.2
	Wheat	
100% NP	18.3	22.5
100% NPK	26.5	33.5
50% NPK	13.1	14.0
150% NPK	17.9	22.4

100% NPK represents recommended dose; 50% and 150% NPK represent ½ and 1.5 times the recommended dose

Conclusions

The fertilizer consumption in India during the last 40 years has increased dramatically but the response ratio (kg grain per kg NPK) for food grain production has declined from 48 in 1970-71 to 10 in 2007-08. The decline in response ratio could be ascribed to gradual decline in the indigenous supply of soil nutrients leading to macro- and micronutrient deficiencies due to inappropriate or imbalanced fertilizer application and little recycling of organic sources. While there is wide scale adoption of blanket fertilizer recommendation and to a lesser extent of soil-test based fertilizer adjustments, there is a need for site-specific nutrient management for balanced fertilization. These observations emphasize the need to monitor soil fertility and emerging nutrient deficiencies and to adopt appropriate management practices for improved nutrient use efficiency. Soil test methods for soil fertility evaluation and for formulating fertilizer recommendations must be augmented with other chemical and biological fractions to achieve higher FUE.

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Challenges for nutrient management in Bangladesh

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Abstract Present and future nutrient management challenges in Bangladesh have been reviewed. The major challenges include: distribution and marketing of fertilizers to the farmers in time of needs; soil fertility constraints; soil and crop needs based recommendation; imbalanced use of fertilizers; insufficient use of organic manure, biofertilizers and plant growth regulators; strengthening soil testing services and maintenance of soil health. Marketing and distribution of all fertilizers except urea in the country are now made by the private sectors under the supervision and control of the government. Most of the demand of fertilizers is met up through import. There is intensive cropping to meet growing demand for food in Bangladesh that led to continuous mining of nutrients from soil. Most of the soils are depleted and are in urgent need of replenishment with organic manure and nutrients (fertilizers). Recent high prices of phosphate and potash fertilizers, and other secondary and micronutrients have forced farmers to cut down their applications. Only exception is N, because urea continues to be under heavy subsidy regime. This has caused severe imbalances in nutrients use. Adoption of integrated nutrient management based on close matching of their addition and removal would be the best way to maintain optimum soil fertility and crop productivity. The government should encourage the farmers to use organic manure, and bio-fertilizers in an effort to reduce the application of chemical fertilizers. Soil testing services need to be strengthened which can ensure efficient use of liming and nutrients. Short-term and long-term appropriate actions have been suggested to face the present and future challenges for nutrient management in the country.

Keywords Balanced fertilization • bio-fertilizers • liming • soil testing • nutrient • fertilizer • soil fertility

Introduction

Bangladesh is facing many challenges; the most important ones are the food production and security for her more than 150 million people in an area of 1, 47,624 km^2 where cultivable land is decreasing and population is increasing. Among the total land resources, 8.29 million ha are used for agriculture and 2.40

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million ha are forest (including community forest and village forest). Bangladesh is also now passing through a phase of ecological deterioration leading to loss of plant cover thus lowering organic matter content of the soil, reduction in varietal diversity, lowering water-holding and fertility of the soils, lowering ground water table, loss of wetlands, and many others (Islam et al. 2008). The process of ecological deterioration is negatively affecting the already fragile livelihood of the rural poor and lowering land productivity level. With an ever-increasing population and limited cultivable land, Bangladesh is forced to maximize crop yields per unit area through intensive use of land and soil resources. Moreover, in recent years there has been a shift in the cropping pattern. In many places, because of high demand for poultry feeds acreage under high nutrient demanding hybrid maize is expanding. As a result, continuous mining of nutrients from the soil system is going on. Under such situations, integrated nutrient management is considered one of the best ways to arrest fertility degradation as well as to maintain sustainable productivity of soils. This paper describes the challenges of the nutrient management in Bangladesh agriculture.

The challenges

The major challenges of nutrient management include timely supply and availability of fertilizers at the doorstep of the farmers, recommendation based on soil and crop requirements, use of organic manure, biofertilizers and plant growth regulators, strengthening soil testing services and maintenance of soil health.

Fertilizer use

Fertilizer supplies plant nutrient and is considered one of the key inputs for increasing crop yields and its contribution to crop production is about 50-60%. The use of chemical fertilizers in subsistence and food deficit East Pakistan (now Bangladesh), which began in 1951, increased steadily with time after introduction of modern varieties and reached peak value of about 4.45 million tons in 2008-09 (Table 1). The Department of Agricultural Extension on the basis of nutrient needs and crop production projections usually calculates fertilizer demand. There is huge gap between productions (1.7 million tons) and demands (4.45 million tons). Timely supply of locally produced and imported fertilizers at the farm gates are handicapped by various constraints that result in crisis.

Fertilizer distribution system

Marketing, promotion and distribution of almost all fertilizers except urea in the country are now controlled by private sectors. The transition from government to private sector passed through various phases of experimentation and took about 40 years to complete. Presently, all fertilizer requirements of the country such as TSP, DAP, MOP and urea (about 40-50%), etc. are met through import by the private companies. Out of total requirement of urea (2.52 million tons during 2007-08) only 1.45 million tons and small amount of TSP (50,000 tons) as well as SSP (0.10 million ton) were produced within the country from six urea fertilizer factories and TSP Complex of Bangladesh Chemical Industries Corporation (BCIC). Urea production and import is always controlled by the government, and is distributed to the farmers in the country through 4850 BCIC appointed dealers at heavily subsidized rates. Total production capacity from 6 BCIC's urea fertilizer factories is 1.70 million tons, although installed capacity is about 2.30 million tons. The private importers import TSP, DAP and MoP from USA, Tunisia, Australia, Jordan, Morocco, CIS and China according to the annual needs of the country.

Table 1 Fertilizer use in Bangladesh during the last eight years ('000' Mt)

Year	Urea	TSP	DAP	SSP	MOP	Gypsum	Ammonium sulphate	Magnesium sulphate	Zinc sulphate	NPKS	Total
2001-02	2247	425	127	127	222	96	15	10	13	13	3295
2002-03	2239	405	112	130	250	120	30	10	14	10	3320
2003-04	2324	361	90	148	240	140	15	10	14	13	3355
2004-05	2523	420	140	170	260	135	16	10	14	26	3714
2005-06	2451	436	145	130	290	104	10	10	20	99	3695
2006-07	2600	340	115	125	122	26	25	12	20	160	3543
2007-08	2515	325	122	115	230	72	26	15	25	120	3565
2008-09	2850	500	200	100	400	150	25	20	50	150	4445

Fertilizer subsidy

The prices of TSP, DAP and MOP increased abruptly in the international market at the end of 2003 and beginning of 2004. Due to such high price hike, the balanced use of fertilizer was being seriously affected. The government in consultation with Bangladesh Fertilizer Association (BFA) decided to provide 25% subsidy on these fertilizers. During 2004-05 and 2005-06 the government provided US $ 37.31 and 53.04 millions as subsidy for the phosphate and potash fertilizers, respectively. The government has been providing heavy subsidy on urea fertilizer, which provides the key nutrient nitrogen, critically deficient in the country's soils. The present price of urea per ton at the mill gate is US$ 142.86 and at the buffer gate US$ 152.86. The dealer can sell urea among the farmers at the cost of US cents 15-17 per kg.

Present soil fertility status

Although Bangladesh is a small country, it has wide variety and complexity of soils at short distances due to a diverse nature of physiography, parent materials, land types, and hydrology and drainage conditions. Under intensive cropping, continuous changes are taking place in the soil fertility status due to organic matter depletion, nutrient deficiencies, drainage impedance/water logging followed by degradation of soil physical and chemical properties as well as soil salinity/acidity. The fertility status of Soils of Bangladesh is extremely variable. Most of the soils are depleted and are in urgent need of replenishment with organic manure and fertilizers if projected crop production target is to be obtained.

Nitrogen

Nitrogen is generally considered as the key nutrient in agriculture in Bangladesh because soils are low in N. Most of the agricultural soils are critically deficient in N. The main reasons for N-deficiency are because of intense rate of decomposition of organic matter, rapid removal of mineralized products under excessive leaching condition and crop removal. Total-N content in soils of Bangladesh ranges from 0.032% in the Shallow Red-Brown Terrace Soils to 0.20% in Peat Soils. The approximate values of total-N used to interpret soil test values are; Low: 0.09-0.18 %; Medium: 0.18-0.27%; and Optimum: 0.27-0.36% for upland crops in loamy to clayey soils. In light textured soils, somewhat lower values are used to interpret the soil test results for upland crops. For wetland rice, soil test values for N interpreted as low, medium and optimum are 0.09-0.18, 0.18-0.27 and 0.27-0.36%, respectively, irrespective of soil texture. The soil-testing laboratories of the NARS institutes use these critical levels for total-N in soil.

Except few leguminous crops, all other crops respond to applied N irrespective of soil types, growing seasons and cultivars used. Practically high yielding varieties of different crops such as wheat, maize, potato, sweet potato, cabbage, brinjal, tomato, cauliflower and banana are highly responsive and need ample supply of fertilizer N to attain their yield potentials; while cotton, tobacco, mustard and sugarcane are substantially responsive. Pulses and other legumes are less responsive to applied N in soils of Bangladesh. For some leguminous crops a starter N dose is considered essential for higher nodulation and production.

Responses of applied N to high yielding varieties of rice have been studied extensively throughout the country by a series of fertility trials. The average yield increase due to fertilizer N varies from 30 to 75% (BRRI, 2009). In some cases, without applied N high yielding varieties of rice fail, while application of 100 kg N ha^{-1} along with other nutrients resulted in a very successful yield of 6-7 t ha^{-1}. The field trial conducted by Parul (2008) showed that with 120 kg N ha^{-1}, it was possible to obtain more than 7 t ha^{-1} grain yield from BRRI dhan29 (Table 2).

Phosphorus

Phosphorus is the second most important nutrient element limiting successful crop production. It becomes unavailable or fixed in the soils through a variety of ways.

Table 2 Grain and straw yield of BRRI dhan28 and BRRI dhan29 as affected by different N rates

N rate	BRRI dhan28		BRRI dhan29	
	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})
N0	2160d	2605d	2600f	2858f
N40	3640c	3598c	3862e	4053e
N80	4710b	5140b	6000c	5620d
N100	5600a	5753a	6640b	6465c
N120	5712a	6095a	7230a	7468ab
N140	5642a	6000a	7300a	7648a
N160	5340a	6063a	7130ab	7740a
N200	4039c	6525ab	5400d	7843b
CV%	6.55	7.10	5.88	6.11

In acidic terrace and brown hill soils, phosphorus is largely fixed by iron and aluminum oxides at low pH, while in calcareous soils fixation occurs by calcium-magnesium carbonates. The net result of fixation is a decrease in the immediate availability of native and applied phosphorus. In medium and heavy textured soils, the available P contents up to 7.50 mg kg^{-1} soil is interpreted as low, 15.1-22.5 mg kg^{-1} soil as medium and 22.5-30.0 mg kg^{-1} soil as optimum for upland crops. In light textured soils, somewhat lower values are considered to interpret soil P as low, medium and high. For wetland rice, soil P contents of 6.0-12.0 mg kg^{-1} soil are considered as low, 12.1-18.0 mg kg^{-1} soil as medium and 18.0-24.0 mg kg^{-1} soil as optimum. The critical level of P by the Olsen method, which is extensively used for rice, has been considered as 8.0 mg kg^{-1}.

Appreciable response of wetland rice to P fertilization is rarely observed in Bangladesh soils. On the other hand, P is considered as one of the major constraints to successful production of legumes and upland crops such as wheat, maize, chickpea, groundnut, cotton, mustard, brinjal, tomato, lady's finger etc. Significant role of phosphate application in sustaining and building up soil fertility for various upland crops is well recognized.

Potassium

Potassium is the third major plant nutrient recently identified as deficient in most Bangladesh soils. The previous idea about the sufficiency of potassium in soils of Bangladesh might be true for local crop varieties with low yield potentials. Yield of 1 t ha^{-1} of wheat and 2 t ha^{-1} of rice can be obtained without the application of K fertilizers. The crop intensification with high yielding and hybrid varieties has shown widespread deficiency of potassium in soils of Bangladesh on potato, sweet potato and other root crops, sugarcane, fruit, onion, garlic, fiber crops and HYV of cereals. It has been recorded that a 5 t ha^{-1} rice crop will remove more than 110 kg K which is to be made available to plants in less than 3 months time and many of our old and highly weathered soils may not have potential to supply K at this rate.

Alluvial soils of Bangladesh are comparatively rich in potash bearing minerals than the terraces that are older and show evidences of extensive weathering of 2:1 type minerals and potash bearing minerals. These soils may not release K fast enough to match the crop requirements especially for the modern varieties to sustain yields. Potassium may also be leached and deficiency of K may become a production constraint in light sandy soils of recent alluvium with high percolation rate (72 mm day^{-1}). The critical levels of potassium for soils of Bangladesh have been determined 35.1-70.2 mg kg^{-1} soil as low, 70.2-105.3 mg kg^{-1} as medium, 105.3-140.4 mg kg^{-1} as optimum and above 140.4 mg kg^{-1} high.

The report of a field trial conducted by BRRI (2009) shows that during the boro season of 2008, application of K fertilizer significantly increased the grain yield of all tested genotypes (Table 3).

Table 3 Effect of K rates on the grain yield of *boro* varieties at BRRI farm (BRRI 2009)

K rate (kg ha^{-1})	Grain yield (t ha^{-1})			
	BRRI dhan36	BRRI dhan45	Hybrid-EH$_1$	Hybrid-EH$_2$
0	1.86	2.86	3.64	3.08
20	5.01	5.70	6.40	6.48
40	5.58	5.04	5.62	6.22
60	5.90	5.93	5.92	6.00
80	5.87	6.09	6.27	6.46
LSD (0.05)	0.64			
CV (%)	7.3			

Sulphur

Sulphur has been recognized as the fourth major nutrient limiting crop production as early as 1980. In the past very little attention was paid to this nutrient until 1977 when sulphur deficiency in wetland rice was first detected at the Bangladesh Rice Research Institute (BRRI) farm and on nearby farmers' fields. Since then sulphur deficiency in soils of Bangladesh is becoming widespread and acute. Available S varies widely and ranges from 2 to 75 mg kg^{-1}. The problem is more severe in wetland rice than in upland crops as anaerobic condition, under which rice is grown, reduces sulphate and makes it unavailable to plants. Among the upland crops, oilseeds are most affected by S deficiency problems. Beneficial effects of sulphur fertilization have been observed on mung bean, black gram and chickpea. The critical level of sulphur for soils of Bangladesh has been determined as 10 mg kg^{-1} soil.

Calcium and magnesium

The pH in the soils of Bangladesh ranges between 5.8 and 7.0 (with exception of acid hill soils and calcareous soils). Thus, most of the soils have adequate Ca and Mg saturation on the exchange sites. Recent investigations have reflected that acid hill soils and Old Himalayan piedmont soils are extremely low in exchangeable Ca and Mg. The critical levels are 800 and 200 mg kg^{-1} for Ca, and 480 and 120 mg kg^{-1} for Mg. Magnesium deficiency problems have been observed on potato, cotton, sugarcane and tea grown on these soils and added Mg has brought about an appreciable increase in yields. Although Ca is also inadequate in these soils, applications of TSP and gypsum to supply P and S satisfactorily meet Ca demand of crops, thus correcting Ca deficiency properly.

Zinc

The importance of zinc in crop nutrition has received considerable attention during eighties in the country. The incidence of zinc deficiency is widespread in most calcareous and alkaline soils. The problem is more acute in wetland rice culture. The critical levels of available soil zinc content as established by different extracting procedures are 1 mg kg^{-1} for light textured soils and 2 mg kg^{-1} for heavy and calcareous soils. The critical level of Zn in rice plant tissue is generally considered as 20 mg kg^{-1}. Yield responses of rice to zinc fertilization have been well documented in different soils of Bangladesh where zinc contents were below the critical level.

Boron

Although taken up in tiny quantities, boron deficiency may lead to serious consequences regarding economic yield of various crops. Boron deficiency in Bangladesh was first observed in reverine soils of Teesta on wheat causing sterility in grains (Islam 2006). Light textured soils of the country are deficient in available boron where significant leaching loss of borate ions might have depleted soil boron level. The available boron content of the major soils of Bangladesh varies between 0.1 and 1.9 mg kg^{-1} . But most of the light textured soils of Rangpur, Dinajpur and terrace soils of Gazipur and hill soils of Srimangal contain low level of available B (0.1-0.3 mg kg^{-1}). The critical level of available soil boron used to interpret the soil test result is 0.2 mg kg^{-1}. However, Studies showed that sterility problems in wheat, chickpea and mustard grown on sandy soils of Rangpur were significantly improved by the application of boron. Wheat yield after boron treatment was increased by more than 50% and was contributed by increased number of grain per spike. Thus, it has been reported that boron deficiency might be a causative factor for sterility problems. Yields of vegetables like cauliflower, cabbage, broccoli and tomato were found to increase (14-52%) due to B fertilization.

Other micronutrients

Recently Cu and Mn application in calcareous Soils have appeared to be beneficial for higher yield in some field trials. Recent studies have also indicated that Mo deficiency is widespread in cabbage and legumes like groundnut in acid soils. Appreciable yield increases of these crops in presence of added molybdenum have also been recorded. Deficiency of Cl^{-1} has been detected in coconut and betel nut plants. But proper potassium fertilization with muriate of potash prevents the occurrence of Cl^{-1} deficiency problems in most cases. Iron is the only micronutrient that is abundantly present in available form in the soils of Bangladesh.

Present supply and availability situations

The Ministry of Agriculture, in consultation with the Department of Agricultural Extension fixes up monthly as well as annual requirement of fertilizers. Besides demand requirement, the Ministry also makes a total exercise on production, import and price fixation.

Domestic production

In Bangladesh, urea, TSP and SSP are produced in local industries, which can partly meet the total demand of the country (Table 4). About 60,000 tons of phosphorgypsum is produced as a byproduct of TSP factory. All the six fertilizer factories can produce 1.70 million tons of urea, 12000 tons of ammonium sulphate, 50,000 tons of TSP, 0.10 million ton of DAP, and 0.10 million tons of SSP. Additional requirements of urea are met up from import. Additional requirements of TSP, DAP and gypsum are also met by import. All MOP are imported. There are more than 50 small zinc sulphate manufacturing factories in the country which can produce ten thousand tons of granular monohydrate and crystalline heptahydrate zinc sulphate. Some companies produce small amounts of boric acid.

Table 4 Domestic Fertilizer Production during last 8 years (BER 2008)

Year	Production (000 tons)			
	Urea	TSP	SSP	DAP
2001-02	1546	68	120	-
2002-03	2057	65	136	-
2003-04	2164	65	135	-
2004-05	2200	65	134	-
2005-06	1700	60	100	-
2006-07	1700	60	100	100
2007-08	1400	50	100	100
2008-09	1700	50	100	100

Fertilizer types and grades

The farmers of Bangladesh use mainly single or straight fertilizers as sources of plant nutrients. Urea, TSP, DAP, SSP and MOP are the widely used straight fertilizers. Among them, urea shares about 66%, TSP 11%, SSP 4.3%, DAP 4.3% and MOP 9% of the total fertilizer use. Gypsum, ammonium sulphate, zinc sulphate, boric acid, magnesium sulphate and potassium sulphate account for the rest. The government of Bangladesh has recommended 6 crop specific grades of mixed or blended fertilizers for balanced application of nutrient elements in the crop fields. These grades are; NPKS (8-20-14-5) for HYV Rice, NPKS (10-24-17-6) for HYV Rice, NPKS (10-15-10-4) for Sugarcane, NPKS (14-22-15-6) for Sugarcane, NPKS (12-16-22-6.5) for Wheat and other Rabi crops, NPKS (12-15-20-6) for wheat and other Rabi crops. Among the six grades, different companies produce only rice grades.

Present challenges of nutrient management

The food requirement of Bangladesh will be double in the next 25 years while its natural resource base will shrink. To keep pace with population growth, yields will have to be increased by 60-70 per cent within that period. Although the total agricultural production has increased significantly, but recently, declining or stagnation of yield of major crops has been recorded in the country. This is due to the cumulative effects of many soil-related constrains. Besides nutrient mining; depletion of soil organic matter, imbalanced use of fertilizers, scanty use of bio and organic fertilizers and poor management practices are the major causes.

According to current statistics, the farmers of Bangladesh use 191 kg nutrients (N 143 kg, P_2O_5 27 kg, K_2O 17 kg and S +Zn + B + others: 4 kg) ha^{-1} $year^{-1}$ from chemical fertilizers, while the estimated removal is around 250 -350 kg ha^{-1}.

Table 5 Nutrient dynamics in *Boro*-Fallow–T. *Aman* cropping pattern (DAE-SFFP 2002)

Nutrient dynamics	N (kg ha^{-1})	P (kg ha^{-1})	K (kg ha^{-1})
Removal			
Nutrient uptake	180	27	180
Leaching losses			
Soil	12	-	6
Fertilizer	17	-	-
Erosion	12	2	12
Gaseous losses			
Organic	24	-	-
N fertilizer	68	-	-
Total Output	***313***	***29***	***198***
Addition			
Fertilizer	170	25	75
Organic manure (5t ha^{-1})	20	12	24
Incorporated crop residue	25	3	25
Non symbiotic fixation	10	-	-
Atmospheric fixation	8	1	2
Sedimentation/weathering	-	2	10
Irrigation water	2	6	21
Total Input	***235***	***49***	***157***
Balance	-78	20	-41

From organic and natural sources about 50-70 kg nutrients are added to the soil system every year. Annual depletion of nutrients (NPKS) in many areas under intensive cultivation ranges between 150 and 250 kg ha^{-1} yr^{-1}. A nutrient balance study made by DAE-SFFP from a typical *Boro*-Fallow–T. *Aman* cropping pattern (10 t grain yields) shows that negative balance of 78 kg N and 41 kg K in a hectare of land are occurring every year (Table 5).

It is quite evident from the study that severe mining of N and K are going on in the soil system. That's why the productivity of the soils is low and decline in crop yields has been recorded in many areas. Since fertile is the fundamental resource for high yield, its maintenance is a prerequisite for long-term sustainable crop production. In view of the deteriorating soil fertility situations in the country, the major challenge is how to arrest or halt the depletion of nutrients from the soil system. The adoption of Integrated Nutrient Management System and Balanced Fertilization Practices are the most important remedial measures that maintain soils in high fertility state.

Adoption of Integrated Nutrient Management System (IPNS)

The adoption of IPNS that combines the use of organic and chemical fertilizers can only provide ideal nutrition for crops (Tables 6 & 7). In Gazipur and Faridpur, application of *Grameen Shakti Jaibo sar* along with 75% recommended doses produced comparable results with 100% recommended doses. However, as expected poultry bioslurry produced the highest yields (Table 6).

Table 6 Effect of *grameen shakti jaibo sar* (organic fertilizer) on the yield of tomato (Islam et al. 2008)

Treatment	Yield (t ha^{-1})		% Increase over control	
	Gazipur	Faridpur	Gazipur	Faridpur
100%RD	64.7ab	73.3ab	183	153
75%RD	56.9c	66.5cd	149	130
50%RD	46.3d	54.9e	103	89
75%RD+CD@5 t ha^{-1}	63.9ab	71.2a-d	180	146
50%RD+CD@10 t ha^{-1}	58.8c	66.8bcd	157	131
75%RD+CD bioslurry@5 t ha^{-1}*	65.1ab	72.9abc	185	152
50%RD+CD bioslurry@10 t ha^{-1}*	61.8abc	66.6bcd	171	130
75%RD+PM@3 t ha^{-1}	64.6ab	70.4a-d	183	143
50%RD+PM@6 t ha^{-1}	60.4bc	66.9d	164	131
75%RD+PL bioslurry@3 t ha^{-1}*	66.6a	75.0a	192	159
50%RD+PL bioslurry@6 t ha^{-1}*	60.6bc	68.0bcd	165	135
Control (native fertility)	22.8e	28.9f	-	-
SE(±)	1.57	2.02		
CV (%)	4.72	5.38		

RD (Recommended dose): N_{150} P_{45} K_{85} S_{20} Zn_3 B_2; CD: Cow dung; PM: Poultry manure; *Grameen Shakti Jaibo Sar

Data in Table 7 showed that an amount of 75% RD of chemical fertilizer in combination with 10 t PM ha^{-1} produced the highest yield of tomato (66.4 t ha^{-1}) while 5 t PM ha^{-1} in addition to 75% RD produced the highest of the second crop-okra, that was statistically identical to 100% RD. Nutrient residue of the first two crops along with supplemental N gave statistically identical yield (34.7 t ha^{-1}) with 100% RD for the third crop- Indian spinach.

Balanced fertilization

Balanced fertilization is the key to successful crop production and maintenance of good soil health. Unfortunately, fertilizer use in the country is generally considered sub-optimal and unbalanced. Looking at the nutrient balanced ratios for the last few years (N: P: K-8.5:1.4:1.0 for 2007-08) the picture appears bleak (BER 2008). During 2006-07 the ratio was 16.6:4.1:1.0 for N: P: K. Application of

Table 7 Yield of vegetables in Tomato-Okra-Indian spinach cropping pattern as influenced by integrated use of chemical fertilizers and organic manure at homestead, Tangail during 2005-06 (Khan et al. 2008)

Treatments	Tomato		Okra		Indian spinach		Yield of crops			Tomato equivalent yield ($t\ ha^{-1}$)
	PM	CD	PM	CD	PM	CD	Tomato	Okra	Indian spinach	
	Org. manure ($t\ ha^{-1}$)						Yield ($t\ ha^{-1}$)			
100%RD	0	0	0	0	0	0	64.2ab	9.7ab	36.2a	102.7
75%RD	10	0	5	0	0	0	66.4a	20.8a	34.7ab	104.5
75%RD	0	10	0	5	0	0	60.2b	18.8abc	32.5abc	95.8
50%RD	10	0	5	0	0	0	58.7b	17.3bcd	30.8bc	91.8
50%RD	0	0	0	10	0	0	53.3c	15.4cd	28.4c	73.1
CV (%)							6.5	9.8	7.3	

RD (recommended dose):N_{150} P_{40} K_{80} S_{20} Zn_2 B_1 for tomato; N_{120} P_{35} K_{70} S_{15} Zn_2 B_1 for okra and N_{120} for Indian spinach

potassium is very low indicating its severe mining from the soil system. It is important to see how close nutrient addition and removal by crops match with each other. During 2005-06, about 1.65 million tons of nutrients from the chemical sources were used, whereas the estimated nutrient removal was more than 2.20 million tons indicating depletion of nutrients in the soils.

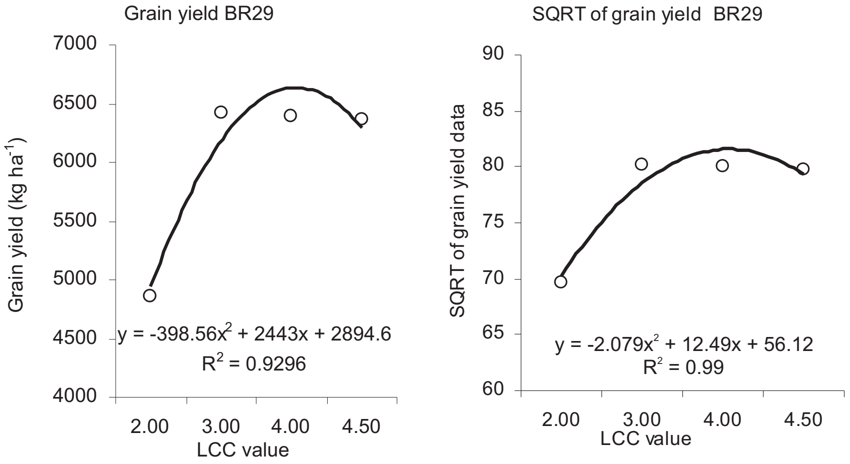
Extension activities for promoting balanced fertilization

Extension activities on balanced fertilization have been undertaken by various research institutes, GO/NGOs and development partners through out the country. Technologies generated on balanced fertilization practices for different crops and cropping patterns at the various National Agricultural Research System (NARS) institutes and also at the Agricultural and General Universities are transferred to the end users through various mechanisms. One of the main mechanisms is the Department of Agricultural Extension, which directly takes the technology to the farmers' fields for demonstration. Besides DAE, different NGOs directly involved in agricultural development activities also take the fertilizer use technology to the doorsteps of the farmers. The different National Agricultural Research Systems (NARS) institutes arrange training programs for extension and NGO personnel through which they are trained about the beneficial aspects of the technology. BARC's Technology Transfer and Monitoring Unit (TTMU) also serve as a vehicle in between research institutes and agricultural development agencies. TTMU also helps transfer of promising NARS institutes' technology to the farmers' fields through different projects funded by the government as well as donors and development partners. International Fertilizer Development Center has been playing a significant role in developing and disseminating fertilizer use technology in the country since long. Other important donor projects such IFAD SAIP, ADB NW Crop Diversification and FAO/UNDP project on food security in DAE are also making significant contribution to agricultural development in the country.

Fertilizer recommendation

Fertilizer recommendation for single crops and cropping system are usually made by following the guidelines clearly stated in "The National Fertilizer Recommendation Guide" which is revised and published from time to time by the Bangladesh Agricultural Research Council in consultation with NARS scientists engaged in soil fertility and fertilizer management research activities. Upazila Soil Use Guide published and updated by SRDI from time to time is also a useful guide for site-specific fertilizer recommendation. Each guide has at least 100-150 site-specific information on soils nutrient status, topography, hydrology, vegetation and drought. Fertilizer recommendations are usually made on the basis of soil fertility classes; yield goals and farmers' management ability. For high yield goal fertilizer recommendation, one should have site-specific information on nutrient status of soils as well as the crops. If the site-specific information on the soils is not available, moderate yield target may be fixed and the information available about agro ecological region in the guide may be used to find out the fertilizer doses.

Fig.1 Grain yield ($kg\ ha^{-1}$) and Square root (SQRT) of grain yield data of BRRI dhan29 as affected by different LCC value based N treatments, BRRI, Gazipur, 2002.



Research on site-specific N management using leaf color chart in Bangladesh is in progress at the Bangladesh Rice Research Institute.

Use of biofertilizers

Use of biofertilzer in Bangladesh agriculture could not yet make any significant contribution. BARI and BINA have been experimenting with different crop specific biofertilizers since 1980. Some of the biofertilizers proved useful for chickpea, lentil, mung bean, groundnut and soybean, which is quite evident from Table 8. Their contribution to yield increases range from 5 to15% where the native population of the microbes is low.

Table 8 Effect of rhizobial inoculums and chemical fertilizers on the seed yield of lentil (BARI 2008)

Treatment	Yield (t ha^{-1})	
	2006-07	2007-08
$N_{24}P_{22}K_{42}S_{20}Zn_5$	1.77c	1.75b
$N_{50}P_{22}K_{42}S_{20}Zn_5$	1.94b	1.65c
$N_{50}P_{22}K_{42}S_{20}Zn_5$+Inoculum	2.22a	1.86a
Farmer's practice ($N_{20}P_{12}K_{17}$)	1.73c	1.56d
CV (%)	4.5	10

In addition to Rhizobia, there are free-living microorganisms like Azotobacter, Clostridium, and Azospirilum in or on soils that can fix atmospheric nitrogen. There is also a group of organisms known as blue -green algae that fix atmospheric nitrogen. N fixed by these organisms play a significant role in meeting the nitrogen requirement of our crop plants.

Use of Plant Growth Regulators (PGR)

The farmers of Bangladesh could not harvest additional yield advantage of crops due to use of plant growth regulators, although the role of growth regulators in various physiological and biochemical processes is well known. Growth regulators are reported to influence seed germination, vegetative growth, nodulation, tuberization, flowering, fruit and seed development, fruit ripening and yield. The studies of Wahida et al.(2006) have confirmed this (Table 9).

Soil testing service

Soil testing service in Bangladesh is weak and not satisfactory up to the standard, as one could have expected after installing all modern equipments and instruments at all the laboratories. SRDI and the soil laboratories at the NARS institutes provide soil-testing services to the farmers at limited scale, although SRDI's 15 regional laboratories located at different parts of the country are designed to analyze at least 75000 samples of the farmers.

Table 9 Yield and seed quality of chili (*Capsicum annum* L.) as affected by different growth regulators.

Treatments	No. of fruits plant^{-1}	Fruit yield plant^{-1} (gm)	Germination (%)	Seedling vigor
Distilled water	71.0 d	146.6 d	65.0 d	275.5 d
10ppm Naa	136.3 a	277.8 a	92.0 a	589.1 a
50 ppm Naa	91.3 c	176.4 c	82.0 bc	522.5 ab
100 ppm Ethophone	107.7 b	221.1 b	67.0 ab	518.8 ab
500 ppm Ethophone	112.3 b	206.0 bc	79.0 c	409.5 bc
1000 ppm KNap	104.3 b	202.0 bc	78.0 c	254.1 d
5000 ppm KNap	103.7 b	189.4 c	79.0 c	358.6 cd
LSD (0.05)	10.19	29.65	7.14	129.9
CV (%)	5.61	8.35	5.05	13.73

The Department of Agricultural Extension with a view to provide soil-testing service to the farmers has procured 460 soils testing kits and distributed among 428 upa-zilas (sub-districts), 20 nurseries and 12 ATIs. After initial runs with the supplied chemicals all the kits now become nonfunctional for want of consumable chemicals and operational funds.

Liming

Bangladesh has great diversity of soils. Except calcareous floodplain and coastal saline soils, all other soils are slightly to strongly acidic. Strongly acid soils are not productive soils. Very strongly acidic soils have been identified from acid sulphate and brown hill areas. Red soils of Madhupur and Old Himalayan Piedmont plain soils in northwestern part of Bangladesh have also been rated as strongly acidic. Because of the increasing cropping intensity and fertilizer use during the last two decades, the acidity has gone up unexpectedly. From every harvest, the crops take up lots of calcium and magnesium. As a result, acidity in these soils is increasing day by day. For every 100 kg use of urea, 74 kg calcium carbonate is needed to reduce the acidity. Application of lime to the soils depends on the intensity of active acidity. Acid Brown Hill soils and Old Himalayan Piedmont Plain soils need dolomite lime to reduce acidity and correct magnesium deficiency. The liming has a favourable effect on the yield of maize on these soil (Table 10)

Table 10 The response of maize to liming in Old Himalayan Piedmont Plain soils (BARI, 2008)

Lime applied (t ha^{-1})	Maize grain yield (t ha^{-1})	
	Lalmonirhat location	Patgram location
0	6.29b	6.46b-
1	-	7.45a
2	8.35a	7.92a-
3	-	7.52a
CV (%)	7.65	10.69

Liming has many favorable functions in the soils. It increases nitrogen and phosphorus availability, makes potassium more efficient, furnishes calcium and magnesium for plant nutrition, encourages activity of beneficial bacteria and reduces the harmful effects of aluminum. Liming also improves the physical conditions of the soils by decreasing its bulk density, increasing its infiltration capacity and increasing its rate of percolation.

Future nutrient management challenges

An overview of the soil fertility issues described above has shown that there exists tremendous opportunities to build a poverty and hunger free Bangladesh if the fertilizer use technology developed by the NARS institutes is disseminated. The soils of Bangladesh are continuously being depleted because of increasing cropping intensity. If appropriate measures are not taken to correct the deficiencies, the soil resources will be degraded. Under such situations, production program of agricultural crops to a level that will ensure food security will be jeopardized. Environmental pollution due to fertilizer use would be minimum if proper methods of soil fertility management were adopted. The following short-term and log-term actions should be undertaken to maintain soil health at a productive state.

Short-term actions

Short term actions include the application of balanced fertilizers to crops /cropping system, site specific fertilizer application through soil testing/leaf color chart, application of USG and UMG to increase efficiency of nitrogen, sufficient application of potash fertilizers to arrest it's mining, strengthening activities of soil fertility and fertilizer management project, production, marketing and distribution of compost, farmyard manure, vermin-compost, bioslurry etc, increasing uses of mixed and DAP fertilizers, undertaking action program for quality control of fertilizers, introduction of pulse crops/sesbania in between two rice crops, introduction of jute in wheat-fellow-rice pattern.

Long-term actions

Includes strengthening Integrated Soil and Fertilizer Management Program, strengthening Coordinated Soil Test Response Studies and strengthening IPNS approach and establishment of IPNS school for the farmers

Conclusions

Timely supply and availability of fertilizers at reasonable prices at the doorsteps of the hard working farmers in the country can only ensure proper nutrient management that is very much needed for the depleted soils for optimum supply of nutrients for successful crop production and maintenance of soil health. At present more than 4 million tons of chemical fertilizers pricing to over US $ 10,000 millions are being used along with 70 million tons of organic manure. The use efficiency of the chemical fertilizers is low and unsatisfactory because of imbalanced or under use/ over use resulting in huge wastage which the country cannot afford. Therefore, the practice of balanced fertilization should receive top priority to sustain/increase crop productivity when food security is so crucial for poverty stricken people, when the country is facing challenges of increasing population and shrinking natural resources including agricultural land and also when there exists big gap between research and farmer's yields.

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Increasing crop productivity through judicious use of potash in Pakistan

Z Ahmad • SM Mian

Abstract Agricultural lands of Pakistan once considered adequately supplied with potassium (K) for crop production are fast losing their soil test K levels due to continuous cultivation of crops without K application. Many crops now respond to K application while its application rate is negligible compared to nitrogen (N) and phosphorus (P). It has been estimated that soil test K levels have declined in various cropping systems ranging from 7 to 49%. Public and private sector stakeholders have joined hand for promoting K use, while its high price, relatively low response in majority of crops and lack of quality premium for growers of cash crops are main constraints in popularity of K application among farmers. On the other hand, crops varied widely in response to K application, ranging from meager one percent in case of maize grown in Rainfed Zone to 30% in case of potato sown in Central and Rice Zones. There is need to intensify extension activities in creating awareness for K use among farmers while government need to subsidize potash fertilizers to sustain crop productivity and soil fertility in Pakistan.

Keywords Crop productivity • potash depletion • soil testing

Introduction

Agriculture provides livelihood to about two-third of country's population while majority of farming units are of only subsistence size and about 80% of farmers have less than 5 hectare (Ha) of land. Such distribution of farming land is the main reason behind overall cropping pattern of the country whereby food crops (wheat, rice, maize etc.) occupy 54% of total cultivated area while cash crops (cotton, sugarcane, potato etc) constitute only 20% (Government of Pakistan 2007). In other words, agriculture is mainly taken as a source to ensure food grain for the family throughout the year, and enough surplus to use as exchange for menial services. Lack of progressive approach in agriculture led to unscientific use of land and other inputs such as fertilizers resulting in average crop yields lower than

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world average by 20-30% and lower by 40 to 50% than their genetic potential as realized by progressive growers (Malik 2008).

Most of cultivated soils of Pakistan have developed from micaceous alluvium – a rich source of potassium (K), and are supposed to have sufficient supply of potassium for optimum plant growth (Bhatti 1978; Mehdi et al. 2001). The need for K is not as widespread as for nitrogen (N) and phosphorus (P), probably due to dominance of hydrous mica in the clay fraction (Ranjha et al. 1993). Recent studies, however, have shown that certain crops grown in wide range of agro-climatic conditions in Pakistan needed K addition to realize the optimum (95% of the maximum attainable) and / or maximum (99% of the maximum attainable) yields (Ahmad et al. 2000). This might have been the result of K mining due to introduction of high yielding varieties in 1960s coupled with increased use of N and P in subsequent years, while K use was not popularized due to lack of response in most crops (Mian and Ahmad 2007). Almost all soils are deficient in N mainly because of arid to semi arid climate leading to high oxidation rate of organic matter, about 90% soils are low to medium in P and around 50-60% are deficient in potassium (Ahmad 2008). Although the fertilizer use in Pakistan is about 130 kg per ha per annum, it is lopsided towards N with respect to P and K (Ahmad 2008). Current N:P:K application ratio (10.0:2.7:1.0) is highly imbalanced with respect to the desired ratio of 10.0:5.0:1.0. The main reason for this imbalance is price parity in case of N compared to P and K. The K lags far behind in this race, which is expected to have negative impact on crop yields, quality of produce, and sustainability of soil fertility of agricultural lands. According to an estimate, soils test K level in Punjab province which is the main agricultural state contributing about 70% to overall agricultural productivity of the country, have declined at average annual rate of 3 mg per kg during last 15 years (Mian and Ahmad 2007). This means a decline of about 60 mg per kg K from Punjab soils during last two decades, and resultantly, soil test K levels once considered adequate for plant growth are now nearing the deficiency threshold (Mian et al. 2009).

Public as well as private sector organizations are working hand in hand for promoting balanced use of fertilizers in the country, especially with respect to K, to avoid further loss of soil fertility and overall agricultural productivity. During recent years, extensive research and extension work was carried out to fulfill this objective.

Soil testing and crop response calibration studies

Changing patterns of soil test K

Soil Fertility Research Institute, Punjab (SFRIP) has the mandate to monitor soil fertility levels of agricultural lands in the Punjab province, and to conduct experiments for studying crop responses to applied nutrients. Based on these studies, fertilizer recommendations for various crops are formulated and forwarded to growers through extension workers of public and private sectors.

In a bid to assess changing pattern of soil test K levels, data from samples analyzed for advisory purpose to farmers from two particular years i.e. 1990 and 2005 were used (Table 1). Whole of the province was segregated into four agro-ecological zones: Rainfed Zone comprises of northern parts of the province where rainfall is the only source of moisture for crops, and the cropping pattern consists of wheat during winter and maize during summer. Rice Zone consists of irrigated north-eastern parts of the province famous for the production of fine rice during summer while wheat remains the main winter crop. The Central Zone comprises of central irrigated districts of the province where wheat is the major winter crop while other crops include maize, sugarcane, potato, pulses and fodders. The Cotton Zone falls in southern parts of the province where wheat-cotton is the major crop rotation.

Table 1 Soil test potassium (mg kg^{-1}) in various crop zones of the Punjab through 1990 to 2005.

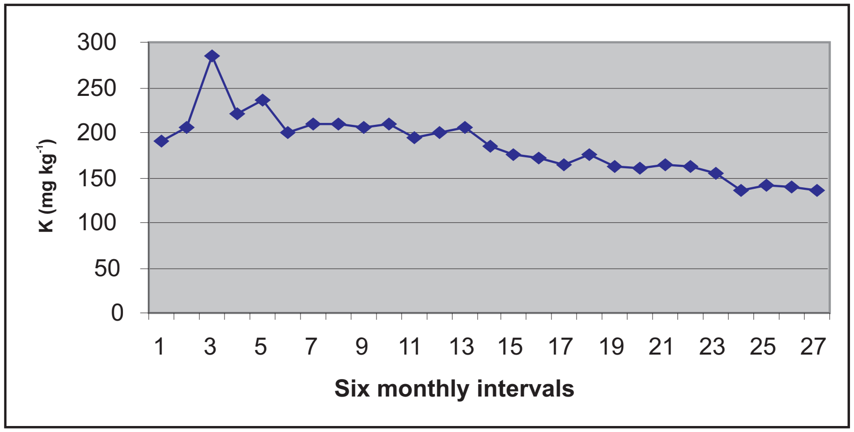
Zone	1990			2005			Per cent decrease
	No. of samples	Mean	SD	No. of samples	Mean	SD	
Rainfed	1500	114	34	1550	106	21	7
Rice	1400	176	71	1645	132	90	33
Central	2670	295	153	3200	198	83	49
Cotton	1658	210	15	2280	165	32	27

A consistent decline was evident in soil test K levels in all cropping systems ranging from 7 to 49% in the order of Central > Rice > Cotton > Rainfed (Table 1). The fifteen years of continuous cropping caused K levels of Rice and Cotton Zones to slide down from high K level category to medium category, considering 180 mg per kg as the threshold (Akram et al. 1994). Although soils of Central Zone are still categorized as high in K levels, a decline of 49% during thirteen years is alarming, and may cause soils to become deficient in K soon if potashic fertilizers are not given their due share in farmer input practices. The trends are explainable in the light of farming practices of the zones. Rainfed zone is characterized by very low cropping intensity (about 50%) and low crop yields, due to unavailability of irrigation water – thus resulting in minimum decline of soil test K levels. Rice and Cotton Zones, on the other hand, are characterized by a cropping intensity of about 130% while crop yields are also higher than in Rainfed Zone. Food crops are predominantly grown and farmers have tendency of low P and no K application because of nutrient price factor. In Central Zone, fertilizer addition per hectare is higher than other three zones on comparative basis

(Government of Pakistan 2007). A high cropping intensity coupled with multi cropping system including exhaustive crops like potato and maize may be the cause of K-depletion at higher rate in Central Zone.

The high values of standard deviation (SD) of the data is due to extreme low or high values. These extreme values may impart a dragging effect on mean values, and thus could paint a different picture of the distribution of K level in test Zones. A model site, therefore, was selected at Sultanke, Lahore for monitoring changes in soil test K levels on six monthly intervals for a period of thirteen years starting from 1990-91 (Fig. 1). During this time period, normal rice-wheat cropping was practiced by applying only N and P, as per farmers' practice of that area. This site also depicted a declining trend in soil test K level and since 1998, remained consistently below 180 mg kg^{-1}, which is considered as the threshold in categorizing the soils into responsive and non-responsive and confirmed by predicting wheat and rice responses to applied K (Akram et al. 1994). It can also be observed that rate of mining K from soil was rapid once it crossed the critical limit.

Fig. 1 Soil test K at model site (Sultanke, Lahore) during 14 years (1990-2003)



Crop responses to applied K

Yield data of field experiments conducted throughout the Punjab during 2004-2005 were used to fetch response magnitude of major crops to applied K. These experiments were conducted under the auspices of SFRIP, laid out according to randomized complete block design (RCBD) on farmer fields by applying N and P at rates recommended for these crops by Agriculture Department.

The results of 514 replicated trials envisaged 5-6% response in case of wheat to the application of 120 kg K_2O ha^{-1} in all four cropping Zones. Consistency of wheat response to K addition across zones indicates that soil properties like types and amounts of clay were almost identical in these zones for K release to wheat. Maximum response of rice to applied K (6%) was observed in Rice Zone, with the application of 120 kg K_2O ha^{-1}. In Central and Cotton Zones, 150 kg K_2O ha^{-1} was required to maximize the response, which indicated that soils and climatic conditions of these Zones are not to the mark of suitability for rice. In the Punjab, cotton is grown on diversity of soils with varied levels of soil test K, in Central and typical Cotton zones. The results of 165 field trials conducted in Cotton Zone and 44 in Central Zone indicated 1.3 times higher seed cotton production in Cotton Zone than in Central Zone. Response magnitude due to 120 kg K_2O ha^{-1} was also higher (8%) in Cotton Zone than 6% in Central Zone. Maize responded well to K application at the rate of 150 kg K_2O ha^{-1} in Central (8%) and Cotton (12%) zones, while the magnitude of response was lower (4%) in Rainfed Zone.

Response of potato and sugarcane to applied K

The demonstration trials on farmer fields during 2005 to 2008 conducted by Engro Chemical Pakistan Limited (ECPL) on potato and Sugar industry on sugarcane in Rice and Central Zones indicated that both these crops respond positively to K application in terms of yield while quality of sugarcane crop measured in terms of sucrose contents also improved (Table 2). The economics of K application also proved beneficial for growers as realized by calculating value:cost ratio, which ranged 1.5 to 3.3 in case of sugarcane and 2.5 to 7.8 in case of potato in these trials.

Table 2 Sugarcane and potato response to applied K at farmer fields.

K application	Sugarcane			Potato	
	No. of trials	Average yield (t ha^{-1})	Sucrose (percent)	No. of trials	Average yield (t ha^{-1})
0 K	15	34.60	8.40	21	13.59
+ K		40.39	8.95		17.66

Extension services for promoting K usage at farm level

Both public and private sectors are doing extension work for promoting K use on crops in Pakistan. Fertilizer industry being a major stakeholder in agriculture sector and few other agro based industries especially sugar industry and fruit exporters (being direct beneficiaries of improved produce quality) are major players in private sector promoting balanced fertilizer use including K. Jointly with Public Sector Extension Departments, these organizations reach farmers through mass and individual contacts such as farmer gatherings, seminars, demonstration plots, and group discussions, promotional print materials, print and electronic media etc. In addition, institutions those purchase farmer produce at harvest such as sugar and cotton industries and financial institutions like banks extend credit facilities to growers in their areas for purchase of fertilizers. These institutions influence farmers' choice of nutrients to be added by offering 'credit in kind' instead of 'credit in cash'.

There are, nevertheless, many constraints in promoting K application among farmers in a country like Pakistan where majority of farmers are doing subsistence agriculture. Unpredictable produce prices in case of rice and wheat, lack of quality premium for farmers in cash crops like sugarcane, cotton, vegetables and fruits, and ever increasing prices of P and K fertilizers in international market are few important factors restricting K use in Pakistan.

The way forward

Recent focus on promoting balanced use of fertilizers especially K at all levels has resulted in increased awareness among farmers on its importance. Economical reasons, nevertheless, often act as the driving force behind decision making by the farmers on choice of inputs to be applied to a crop. There is a need to enhance the momentum of K acceptability by common growers so that rate of K mining from agricultural lands can be checked. In the wake of unprecedented price increase of K fertilizers during last two years (2008-09), it is imperative to subsidize these fertilizers as is the case in many developing countries such as India and Iran. Marketing system of agricultural products need to be tuned on the basis of produce quality, especially in case of cash crops. There is likewise need to reduce margins earned by middle men in the markets so that farmers get rightful benefits of their inputs. Fertilizer recommendations for at least cash crops, which are grown by progressive growers need to be tuned on soil test basis rather than giving generalized or Zone based recommendations. A web based system developed by SFRIP may help achieve this objective while their network of laboratories may provide testing facilities to interested farmers. Agro based industries such as Sugar Industry should involve itself more in research and development than just giving loans to growers. Fertilizer Industry should ensure availability of easy, economical and viable options such as tailor made blends of nutrients for various soils, crops and categories of farmers at all times.

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Rice-maize systems of South Asia: Current status, future prospects and research priorities for nutrient management

J Timsina • ML Jat • K Majumdar

Abstract Rice (*Oryza sativa* L.) and maize (*Zey mays*) are grown in 3.5 million hectares (Mha) in Asia that includes 1.5 Mha in South Asia. These crops are grown in sequence on the same land in the same year either in double- or triple-crop systems to meet the rice demand of a rapidly expanding human population and maize demand of livestock and poultry. The objective of this review is to provide a comprehensive overview of the current state of technical knowledge on agro-ecosystems and adaptation, area and distribution, yield potential and yield gaps, and nutrient management for rice-maize (R-M) systems in South Asia. Rice-maize systems are emerging all around South Asia but in particular are developing quite rapidly in Bangladesh and South and North India. Yield potential of rice and maize, as estimated by ORYZA2000 and Hybrid Maize models, reaches up to 15 and 22 t ha^{-1}, respectively. However, data from several environments in India reveal gaps between potential and attainable yields of maize of upto 100% and between attainable and actual yields of upto 25-50%. Nutrient demand of R-M system is high due to high nutrient removal by high-yielding maize. Nutrient balance studies for these highly-productive and nutrient-extractive systems are scarce in South Asia. The review outlines principles of nutrient management for R-M systems, and identifies development, refinement, and dissemination of the integrated plant nutrition system technologies based on site-specific nutrient management principles as priorities for future research to increase yield, profitability, and sustainability of R-M systems.

Keywords Rice-maize • yield potential • yield gaps • South Asia • integrated plant

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Introduction

Rice, maize, and wheat are major cereals contributing to food security and income in South Asia. These crops are grown either as a monoculture or in rotations in tropical and sub-tropical environments of South Asia. In the irrigated and favorable rainfed lowland areas, rice-rice (R-R), rice-wheat (R-W), and rice-maize (R-M) are the predominant cropping systems. Rice-rice is common in tropical climate with distinct dry and wet seasons such as in South India, and in sub-tropical areas with mild cool winter climate such as in Bangladesh, Eastern India, and Eastern Nepal. Rice-wheat systems are extensive in the sub-tropical areas of the Indo-Gangetic Plains (IGP) of Bangladesh, India, Nepal, and Pakistan (Timsina and Connor 2001) while R-M systems exist in all climate ranging from tropical to sub tropical to warm temperates (Timsina et al. 2010). Rice-maize systems, however, are less extensive as compared to R-W or R-R if total area under these cereal systems is considered. There are mainly three cropping seasons in S. Asia: summer or *kharif* or *monsoon* (or called *kharif-II* or *aman* in Bangladesh) from June/July to Sept/Oct, *rabi* or winter from Oct/Nov to Feb/Mar, and spring or *pre-kharif* or *pre-monsoon* (or *kharif-1* in Bangladesh) from Mar/Apr to May/June. Rice (called transplanted *aman* or T. *aman* in Bangladesh) is the main crop in summer while a wide range of crops, including rice (called *Boro* in Bangladesh, eastern India and eastern Nepal), wheat, maize, winter pulses (chickpea, lentil, field peas), potatoes, and mustard are grown in *rabi* or winter season. In the *kharif-1* or spring season, short-duration crops such as maize, pulses (mungbean, cowpea), and rice (called aus in Bangladesh) are grown. All the three major double-crop systems (R-R, R-W, R-M) often include an additional crop such as potato, lentil, chickpea, mustard, etc. in *rabi,* and jute, maize, rice, mungbean, cowpea, etc. during *kharif-1* or spring season (Table 1).

Much is known about rice and maize production systems separately in South Asia. Also, the other two important systems, R-R and R-W, have been researched and reviewed rigorously (for example, see Timsina and Connor 2001 for a comprehensive review of R-W system). Research on R-M system, on the other hand, did not receive any priority until recently. Consequently, there are only a few published papers in scientific journals, and no critical review papers on any aspects of the R-M systems.

Rice-rice systems differ completely from R-W or R-M systems because in the former both crops are grown under flooded conditions, so root development and water and nutrient dynamics would be similar to both rice crops. In contrast, due to similar growing conditions and altered soil hydrology from flooded rice to non-flooded wheat or maize, R-M and R-W systems would face similar soil physical environment as both wheat and maize roots could break plow pans and roots could grow deeper in the profile. Hence, the soil physical and structural properties under R-M system would be fairly similar to that under R-W system. Timsina and Connor (2001) have critically reviewed the soil physical and chemical properties and associated management for alternating wetting and drying environments of R-W system that could be well applied to R-M system as well. However, in contrast to wheat which is grown only in *rabi* season, maize is also grown during pre-kharif or *kharif-1* (spring) and *kharif* (summer) seasons, especially under rainfed situation. While *kharif* maize is generally grown in uplands or higher landscape fields *kharif-1* maize is grown in low-lying rice fields. Hydrology and transient water logging of maize would vary between *rabi* and the two *kharif* seasons. In *rabi* maize the risk of water logging occurs during emergence and seedling establishment while during *kharif-1,* water logging risk due to pre-monsoon rainfall occurs during reproductive stage. In addition, *kharif-1* crops could also be damaged by heavy storms accompanied by the pre-monsoon rainfall. Transient water logging due to heavy rainfall and heavy storms could be more damaging then transient water logging during establishment of *rabi* maize. Both water logging events could, however, alter soil hydrology and nutrient dynamics both during water logging and during drying following water logging. Such altered hydrology could also bring changes in soil-borne diseases and insects and weed ecology and weeds abundance. Breeding for tolerance to transient water logging for maize would be necessary for successful growing of maize in both *rabi* and *kharif-1* seasons. Conservation agriculture (CA) based agronomic practices such as raised beds and reduced tillage would be potential options help alleviate the risk of water logging in both seasons.

Table 1 Area (Mha) under major cropping systems in four south Asian countries (Source: modified and updated from JK Ladha, unpublished data)

Cropping system	Area (Mha)			
	Bangladesh	India	Nepal	Pakistan
Rice-rice	4.50	4.70	0.30	
Rice-rice-rice	0.30	0.04		
Rice-wheat	0.40	9.20	0.57	2.20
Rice-maize	0.35	0.53	0.43	NA[a]
Maize-wheat		1.80	0.04	1.00
Rice-pulses		3.50		
Rice-vegetable		1.40		
Millet-wheat		2.44		
Rice-potato	0.30	NA		
Cotton-wheat		NA		3.10

[a] Areas exist but data not available

One aspect of R-M system that is different from R-W or R-R system is that the nutrient extraction and nutrient drawdown from R-M system would be much greater due to higher yield of maize. High-yield maize crops would require higher amounts of nutrients than that would be required for rice or wheat. Hence, if fertilizers are not added as per the requirements for high target yield of maize there is a possibility of nutrient mining. Realistic nutrient drawn (especially P and K) factors could be derived for each soil and crop growing environments whereby yield could be optimized and profit could be maximized without substantial mining of nutrients from the soil (Buresh et al 2010). At present, there are no literatures on these aspects of R-M systems. Research is required to understand the various aspects of R-M systems that would improve the productivity, profitability, and sustainability of these systems in South Asia.

The magnitude and intensity of R-M systems in the region depend in part upon soil and climate but, more importantly, on the socio-economic circumstances of the farmers, demand of maize by livestock (especially poultry) sector, and domestic and international markets of maize for food, feed and fuel industries. It should also be noted that the R-M systems are also prevalent in Indonesia and common in China and Vietnam but published literatures are lacking. The objective of this review is to provide the comprehensive overview of the current state of technical knowledge in relation to agro-ecosystems and adaptation, area and distribution, yield potential and yield gaps, and nutrient management of R-M systems in South Asia. The review is based on the existing, limited published and unpublished literature on R-M systems, focusing on nutrient management. The review highlights the issues and priorities for future research on R-M systems in general, and for nutrient management in particular. Separate reviews could be justified for R-M systems in East and Southeast Asia as well as on the socio-economic issues and value chain analysis of rice and maize in relation to nutrient and fertilizer management for these systems.

Distribution of R-M systems and fertilizer use in South Asia

Rice-maize systems are distributed all over South Asia but more particularly in Bangladesh, India, Nepal, and Pakistan (Timsina et al. 2010). Dynamics of the area and productivity of R-M systems in different countries depend on the dynamics of area and yield per hectare of rice and maize in those countries. FAO statistics indicate small increases in rice area in the above four south Asian countries from 1976 to 2006 but the rice production more than doubled due to increase in average yield over the same period. Maize area increased dramatically in Bangladesh, Nepal, and Pakistan but slowly in India. However, production in all countries increased substantially due to increase in area as well as yield per hectare with the use of maize hybrids (www.faostat.fao.org). FAO statistics for fertilizer use for the three major cereals (rice, maize, wheat) over the same period reveal that the trend in consumptions of N fertilizer is highest followed by P and K fertilizers. Fertilizer consumption in India and Bangladesh increased steadily since 1961 until recently but that in Nepal and Pakistan was variable (www.fao.org/site/575/default.aspx). There are common concerns of imbalanced fertilizer use (i.e., very high use of N, less use of P, and negligible use of K, S, and micronutrients), soil nutrient mining, and soil organic matter and soil fertility decline (FAO 2006) in all the four countries.

Yadav and Rao (2001) identified the main maize-based cropping systems in irrigated and rainfed conditions in different agro-climatic regions of India. Cropping systems with rice and maize together in the system are presented from their study in Table 2. The Planning Commission of India has delineated country in 15 broad agro-climatic regions based on physiography and climate, and R-M systems are prevalent in all agro-climatic regions, especially in the IGP (Pandey et al. 2008; Gill et al. 2008a,b). Pandey and Sud (2007) and Singh et al. (2008) also showed prevalence of maize in potato- and rice-based systems in different agro-ecological regions of India. Likewise, R-M systems have been highly intensified and diversified all over Bangladesh. Even within a small district of Bogra in northern Bangladesh, for example, several forms of R-M systems exist with the

Table 2 Main cropping systems involving rice and maize in different ago-climatic zones of India (Source: modified from Yadav and Rao 2001)

Agro-climatic region	Cropping system	
	Irrigated	Rainfed
Eastern Himalayan region	Summer rice-maize-mustard	Sesame-rice+maize
Lower-Gangetic Plain region	Autumn rice-maize Jute-rice-maize	Rice-maize
Upper-Gangetic Plain region	Rice-potato-maize	
Eastern Plateau & Hills region		Rice-potato-maize
Southern plateau & Hills region	Maize-rice Rice-maize	
East Coast Plain and Hills region	Rice-maize-pearl millet Maize-rice Rice-maize Rice-rice-maize	Rice-maize + cowpea
West Coast Plain and Hills region	Rice-maize	Rice-maize
Gujarat plains and hills region		Rice-maize
Island region	Rice-maize	Maize-rice Rice-maize + cowpea Rice-maize-urdbean Rice-rice-maize

use of diverse maize hybrids (Ali et al. 2008; 2009).

Rice-maize agro-ecosystems in Asia

Timsina et al. (2010) have identified four main R-M agro-ecosystems with four broad climates in Asia, of which three exist in South Asia (Table 3). The first agro-ecosystem (tropical, warm, semi arid, no winter) includes locations in southern India with tropical monsoon with a longer dry season. In this agro-ecosystem, both rice and maize are not limited by low temperature and can be grown all year round. Here either the fallows after rice are replaced by a maize crop, or the existing areas under rice-rice-maize and rice-maize-maize systems are increasing in acreage. The second agro-ecosystem (sub-tropical, sub-humid, warm summer, mild cool winter) includes locations in Bangladesh, Nepal, and northern India. In this agro-ecosystem, winter is mild cool so rice maybe limited by low temperature. Maize, however, will perform well due to mild cold winter and long grain-filling period and can replace wheat or Boro rice. The third agro-ecosystem (sub-tropical to warm temperate, sub-humid, warm summer, mild to severe cold winter) has been classified into 2 sub-classes, and includes areas in north and northwest India, Terai and hills of Nepal, and Punjab and Sindh provinces in Pakistan. In this agro-ecosystem, both rice and maize can be limited by low temperature and hence can not be grown for sometime in winter. In all the agro-ecosystems, due to decreased availability of irrigation water, some areas under rice, cotton, and sorghum in summer are already or will likely be replaced by a summer maize crop.

Table 3 Key emerging R-M agro-ecosystems in South Asia (Source: modified from Timsina et al. 2010)

Key features	Current systems	Emerging systems	Key examples
1. Tropical, warm, semiarid, no winter			
Tropical monsoon with longer dry season; both rice and maize not limited by low temperatures and can be grown all year round	Rice-rice Rice-rice-pulses	Rice-maize	Cauvery Delta (Tamil Nadu), Karnataka and A.P., India
2. Sub-tropical, subhumid, warm summer, mild cool winter			
Sub-tropical monsoon with cool winter and summer rainfall; rice but not maize maybe limited by low temperatures	Rice-wheat Rice-Boro rice	Rice-maize Rice-rice-maize Rice-potato-maize	Central, western, and NW Bangladesh; Eastern Terai, Nepal; West Bengal, Eastern UP and Bihar, India
3. Sub-tropical to warm temperate, subhumid, semiarid, warm summer, mild to severe cold winter			
3.1. Sub-tropical monsoon with cold winter and summer rainfall; both rice and maize limited by low temperatures and can't be grown for some time in winter	Rice-wheat	Rice-maize	North and NW India; Central and western Terai and mid-hills, Nepal
3.2. Sub-tropical to warm temperate, semiarid, with hot summer and cool to cold winter; very low rainfall; both rice and maize limited by low temperatures and can't be grown for some time in winter	Rice-wheat Cotton-wheat Sorghum-wheat	Rice-maize Rice-potato-maize	Punjab and Sindh, Pakistan

Why R-M systems are important in South Asia?

Excluding China and Pakistan for which exact data for R-M area are not available, R-M systems currently occupy approx. 3.5 Mha in Asia (Timsina et al. 2010). Excluding Pakistan, area under R-M systems is 1.31 Mha in South Asia (Table 4).

Table 4 Current areas (Mha) under R-M systems in South Asia (Source: modified from Timsina et al. 2010)

Country	Area (Mha)		
	Rice	Maize	R-M
India	43.4	7.80	0.53
Bangladesh	10.5	0.38	0.35
Nepal	1.6	0.90	0.43
Total	55.5	9.08	1.31 (exc. Pakistan)

The highest acreage is in India followed by Nepal. The absolute area under R-M system is less in Bangladesh compared to other south Asian countries but it is increasing rapidly over the past 5-6 years (Ali et al. 2009). Rice-maize systems are practiced mostly in the south (Andhra Pradesh, Tamil Nadu, and Karnataka) and in the northeast (Bihar and West Bengal) parts of India with an acreage of more than 0.5 Mha (Table 5). Andhra Pradesh has the highest acreage under R-M system in South India where this system is rapidly increasing under resource-conserving technologies, mostly zero tillage (Jat et al. 2009). Of the four south Asian countries, R-M systems are rapidly spreading in South India and Bangladesh, driven by the rising demand for maize, especially by poultry sector, and tightening world export-import markets. The recent development of short-duration rice varieties and maize hybrids with improved drought tolerance is also providing opportunities for the expansion of R-M systems into areas of South Asia with insufficient irrigation or rain for continuous rice cultivation.

Table 5 Estimates of acreage (ha) under R-M system in India

State	Area (ha)
Andhra Pradesh	250,000
Tamilnadu	30,000
Karnataka	20,000
Bihar	120,000
West Bengal	60,000
Orissa	20,000
Other states	25,000
All India	525,000

Source: ML Jat 2009, unpublished data

Drivers of change from other systems to R-M systems

Among the three competitive crops (*Boro* rice, maize, wheat) in the *rabi* season in Bangladesh, maize has clear superiority over the other two crops. Though hybrid maize requires high input, especially nutrients, it has a very high output that makes it over twice more profitable than wheat or *Boro* rice (Ali et al. 2008; 2009). Maize also requires far less water than *Boro* rice and produces consistently much higher yield than *Boro* rice and wheat. In particular, wheat is often vulnerable to temperature fluctuation resulting in shriveled grains and poor yield. Besides, maize has fewer pest and disease problems than *Boro* rice and wheat.

Maize needs around 850 l water per kg grain production (with 2-4 irrigations) compared to 1,000 l kg^{-1} wheat grain (1-3 irrigations) and over 3,000 l kg^{-1} rice grain (with 20-35 irrigations) for *Boro* rice (Ali et al. 2009). The high financial and environmental costs of irrigating *Boro* rice from electric or diesel pumps is an increasing concern. There are increasing evidences from Bangladesh that arsenic (As) moves along with irrigation water from soil to the plant and then to the grain. Thus, there is a greater chance of As accumulating into the soil, its uptake by the plant, and entering into the food chain through *Boro* rice cultivation (Duxbury and Panaullah 2007). Thus, growing *rabi* maize may be environmentally safer due to less water requirement and less chance of As accumulation in soils and plants and its subsequent transport to food chain. Where soils are already contaminated with As, maize can be grown instead of *Boro* rice as an As management option.

Similarly maize is considered to be a better alternative to wheat or *Boro* or *rabi* rice due to several reasons: (i) wheat encounters several biotic stresses, and most importantly, abiotic stresses due to terminal heat stress in the IGP, (ii) evidences of declining yield of *Boro* rice in West Bengal and Orissa, and (iii) water scarcity in peninsular India affecting yield of *rabi* rice in Andhra Pradesh and Tamil Nadu. Peninsular India and Bangladesh are considered to be neutral environments where maize can be cultivated in all seasons and this is emerging as a potential driving force for diversification from the existing cropping systems to a R-M system. A recent study by National Centre for Agricultural Economics and Policy Research (NCAP) in India has also shown an increasing demand for maize by the industry sector which caters to consumer needs like textiles, paper, glue, alcohol, confectionery, food processing, and pharmaceutical industry, etc. (Dass et al. 2008a). Therefore, in the changing farming scenario in South Asia, maize is emerging as one of the potential crops in rice-based systems that can favorably address several issues like food and nutritional security, climate change, water scarcity, farming systems, bio-fuel demand and other industrial requirements.

Yield potential of rice and maize in R-M systems in South Asia: a modeling analysis

Yield potential (Yp) of any crop cultivar/hybrid for a site (called site Yp) and for a given planting date is the yield achieved when grown in environments to which it is adapted, with nutrients and water non-limiting and pests and diseases effectively controlled (Evans and Fischer 1999). Yield potential will be different for different varieties and for different planting dates. Attainable yield (Yat), generally set at 80-90% of Yp, is average grain yield in farmers' fields with best management practices and without major limitations of water and nutrients. Attainable yield can be limited by variety, planting density, water and nutrient management, soil-related constraints (acidity, alkalinity, salinity, etc.), and climate-related constraints (flooding, drought, etc.). Actual yield (Yac) is the yield farmers receive with their average management under all possible constraints. Yield potential of any crop species or varieties can be estimated by use of crop simulation models. A detailed study on Yp of rice and maize for R-M systems was done by Timsina et al. (2010) who used the ORYZA2000 (Bouman et al. 2001) and Hybrid Maize (Yang et al. 2004) models and long-term National Aeronautics and Space Administration (NASA) climate data to estimate Yp for several sites in nine Asian countries, including the four south Asian countries reviewed here. In that study, four generic rice varieties differing in maturity (extra short-, short-, and long-duration) were created by calibrating the DVRJ (development rate during juvenile phase), DVRI (development rate during photoperiod sensitive phase), DVRP (development rate during panicle development phase) and DVRR (development rate during reproductive phase) coefficients used in the model. Coefficients for an intermediate maturity type as used for IR72 were adapted from Bouman et al. (2001). The growth durations for extra short-, short-, intermediate-, and long-duration varieties in the four south Asian countries ranged from 75 to 110 days, 90 to 125 days, 110 to 150 days, and 130 to 180 days, respectively. Mean Yp of extra short, short, intermediate, and long-duration rice varieties across R-M agro-ecosystems, as predicted by ORYZA2000, ranged from 0.6 to 9.0, 0.7 to 10.8, 0.6 to 12.8, and 0.7 to 17.6 t ha^{-1}, respectively (Table 6). There were large differences in Yp amongst sites within a country, amongst the countries, as well as amongst planting dates at each site (Timsina et al. 2010). For each site, Yp was highest for long and lowest for extra short-duration varieties. The large ranges in Yp for different varieties were associated with large variations in growth duration, total intercepted solar radiation, and growing season mean temperature leading to differences in grain-filling period. In the tropical to sub-tropical climate, Yp was highest for Dinajpur in Bangladesh and Begusarai in Bihar followed by Bogra in Bangladesh. In the sub-tropical to warm temperate climate, Yp was highest in Punjab in India followed by Chitwan in Nepal. Yield potential in Pakistan was intermediate.

For maize, four hybrids differing in growing degree days (GDD), defined as cumulative degree days from seeding to physiological maturity, ranging from 1300 to 1800 GDD, were used. Yield potential of the four hybrids ranged from 7.1 to 19.7 t ha^{-1} in India (with 1400 to 1800 GDD), from 8.7 to 20.4 t ha^{-1} in Bangladesh (with 1500 to 1800 GDD), from 5.8 to 22.4 t ha^{-1} in Pakistan (with 1300 to 1700 GDD), and from 11.1 to 32. 7 t ha^{-1} (with 1500 to 1800 GDD) in Nepal (Table 6). Planting during August to November gave exceptionally high yields due to low temperature during grain filling, long growth duration, and large receipts of solar radiation (Timsina et al. 2010). Thus for rabi planting of maize after rice in South Asia, October and November would provide high Yp and would

Table 6 Yield potential (Yp, t ha^{-1}) of rice varieties and maize hybrids for several locations in four south Asian countries (Source: Modified from Timsina et al. 2010)

Country	Location	Rice		Maize	
		Variety	Yp (t ha^{-1})	Hybrid	Yp (t ha^{-1})
Bangladesh	Bogra	Extra short	4.4-8.1	1500	8.8-12.6
		Short	5.2-9.6	1600	9.8-16.8
		Intermediate	6.4-11.0	1700	10.9-18.3
		Long	7.8-11.5	1800	12.0-19.6
	Dinajpur	Extra short	4.5-9.0	1500	9.0-16.5
		Short	5.1-10.2	1600	10.2-18.1
		Intermediate	6.1-12.3	1700	11.2-19.3
		Long	6.2-14.5	1800	12.2-20.4
	Jessore	Extra short	4.3-7.5	1500	8.7-14.2
		Short	5.5-9.0	1600	9.7-16.0
		Intermediate	7.0-10.4	1700	10.7-17.7
		Long	8.2-12.9	1800	11.8-19.0
India	Begusarai	Extra short	4.6-8.9	1500	8.1-14.9
		Short	5.5-9.9	1600	9.2-16.9
		Intermediate	7.4-11.5	1700	10.4-18.5
		Long	6.2-14.8	1800	11.4-19.7
	Aduthurai	Extra short	4.0-6.3	1500	9.1-11.2
		Short	5.4-7.7	1600	10.2-12.5
		Intermediate	6.5-9.7	1700	11.2-14.0
		Long	8.4-11.9	1800	12.3-5.0
	Thanjavur	Extra short	4.1-6.1	1400	9.2-11.1
		Short	5.1-7.5	1500	10.2-12.4
		Intermediate	6.9-9.4	1600	11.1-13.6
		Long	8.7-11.5	1700	12.2-14.7
	Bangalore	Extra short	6.4-7.7	1400	10.0-13.3
		Short	7.9-9.2	1500	11.2-14.9
		Intermediate	10.0-11.5	1600	12.3-16.4
		Long	12.2-13.8	1700	13.6-17.6
	Nalgonda	Extra short	4.8-7.0	1400	7.7-12.6
		Short	5.1-8.3	1500	9.1-14.2
		Intermediate	6.1-10.6	1600	10.0-15.8
		Long	8.2-12.6	1700	10.7-17.0
	Ludhiana	Extra short	3.0-8.8	1500	7.1-16.6
		Short	2.9-10.8	1600	8.2-20.4
		Intermediate	3.0-12.8	1700	9.0-23.7
		Long	2.6-17.6	1800	9.8-26.0
Nepal	Chitwan	Extra short	1.6-8.7	1500	11.3-27.4
		Short	1.7-9.3	1600	13.1-29.7
		Intermediate	1.9-10.9	1700	14.1-31.3
		Long	2.1-14.4	1800	15.4-32.7
Pakistan	Larkana	Extra short	2.1-7.0	1400	6.2-17.2
		Short	2.5-8.0	1500	7.0-19.2
		Intermediate	2.8-9.5	1600	7.8-20.7
		Long	3.8-11.5	1700	8.6-21.9
	Okara	Extra short	0.6-4.7	1300	5.8-17.7
		Short	0.7-5.6	1400	6.7-18.4
		Intermediate	0.6-8.0	1500	7.6-18.4
		Long	0.7-10.0	1600	8.4-22.4

help in successful intensification and diversification of the rice-based systems. Likewise, for *kharif-1* or pre-monsoon season, late March to early May planting would result in reasonably high Yp and the maize crop would fit easily into the rice-based systems. Very long growth duration in warm temperates of Chitwan, Nepal, and two sites in Pakistan resulted in unrealistically high yields due to larger receipts of solar radiation. The Hybrid Maize model needs to be further tested and refined for warm temperate region of South Asia.

Attainable and actual yields of maize in India

The difference between attainable yield (Yat) and actual yield (Yac) of crop species and varieties can be quite large. Attainable yield of maize in farmers' fields, achieved under optimal conditions, can vary significantly across the agro-ecologies mainly due to genotype x environment interactions but also due to confounding influence of biotic and abiotic stresses and agronomic management.

Dass et al. (2008b) reported Yat and Yac of maize from experiments conducted in 13 representative locations in various agro-environments for nine years (1995-2003) under the All India Coordinated Research Project (AICRPM) on maize. The selected locations were first divided into two categories: locations having lower productivity than the national average (Banswara, Udaipur, Godhra, Varanasi, Kanpur and Chhindwara) and locations (Mandya, Arbhavi, Ludhiana, Dhaulakuan, Bajaura, Dholi and Hyderabad) having greater productivity as compared to national average. Data indicated that the Yac is always less than Yat under all the agro-environments due to limited availability of agronomic inputs and their scheduling. Potential for improving Yat was more at the locations of the first group as compared to the locations of the second group. Except Banswara, other locations of the first group showed the potential for achieving Yat of 4-6 t ha^{-1}, while Yac at all the locations of this group was less than half (1-2 t ha^{-1}) of the Yat. It has also been reported that present average Yac at farmers' fields is only about 50% of the Yat, which could be increased through adoption of improved technology. On the other hand, Yat for most locations was about 4.0 t ha^{-1} except for Arbhavi (5.9 t ha^{-1}) in the high productivity group, whereas, Yac at most of the locations of this group was more (1.2–3.4 t ha^{-1}) as compared to the low productivity group (Dass et al. 2008b).

Data from multi-location trials in India in 2007 and 2008 on integrated nutrient management in hybrid maize (HQPM-1) revealed linear yield increase, without any yield plateau, upto 150% of recommended N rate (150:60:40 kg N, P_2O_5 and K_2O ha^{-1}) together with 6 t ha^{-1} FYM, which indicates that more N will be required than the existing rates to achieve higher yield (unpublished data, ML Jat). Grain yield and grain and straw N uptake data on response of 6 hybrids under three nutrient levels (100:50:50; 150:65:65; 200:80:80 kg N, P_2O_5 and K_2O ha^{-1}, respectively), however, reveal highest yield from 150:65:65 treatment and varying responses of different hybrids to the three nutrient levels. Hybrids varied significantly in nutrient uptake indicating their differences in efficiency as well as nutrient requirements (unpublished data, ML Jat). The data reveal that Yat of maize can be quite large, and so yield gap between Yp and Yat, between Yat and Yac, and that between Yp and Yac can be minimized.

Nutrient management for R-M systems

Principles of nutrient management

Rice-maize systems extract large amounts of mineral nutrients from the soil due to large grain and stover yields. Proper nutrient management of exhaustive systems like R-M should aim to supply fertilizers adequate for the demand of the component crops and apply in ways that minimize loss and maximize the efficiency of use. The amount of fertilizer required depends on many factors including the indigenous supply of each nutrient which can be in appreciable quantities (Cassman et al. 1998). Phosphorus inputs from irrigation and rain waters are negligible (Dobermann et al. 1998) but 1000 mm irrigation through surface water may provide up to 30 kg K ha^{-1} yr^{-1} (Dobermann et al. 1996, 1998) and up to 1100 kg S ha^{-1} yr^{-1} (Pasricha 1998). In R-M areas where groundwater is used, K inputs may be much larger than 30 kg ha^{-1}. Thus, to achieve and sustain the high yields currently demanded of R-M systems, emphasis must be upon the nutrient requirements for target yields and nutrient supply by integrated use of indigenous sources, soil organic matter (SOM), farm yard manure (FYM), composts, crop residues, and increasingly, inorganic fertilizers. Fertilizer is the dominant source of nutrients and is required to increase yield of individual crops in R-M systems but should be applied in such a quantity that it becomes profitable and will have least adverse effect on environment. In the exhaustive R-M systems, it is necessary to attend to the distinct requirements and growing conditions of the individual crops. The inclusion of legumes or potato in the R-M system further increases the demand for the macronutrients (N, P, K, Ca, Mg, S) that they require in larger quantities than cereals.

Inorganic fertilizers

Timsina and Connor (2001) devised principles of fertilizer practice required to achieve high efficiency of use and high sustainable yield in R-W systems that could equally apply to R-M systems. Of all the nutrients, nitrogen (N), phosphorus (P), and potassium (K) remain the major ones for increased and sustained productivity. However, the development of high yielding R-M systems will likely exacerbate the problem of secondary and micronutrient deficiencies, not only because larger amounts are removed, but also because the application of large amounts of N, P, and K to achieve higher yield targets often stimulates the deficiency of secondary and micronutrients (Johnston et al. 2009).

Nitrogen management requires special attention so that potentially large losses can be minimized and efficiency can be maximized. During the growing season of rice, the aim of fertilizer management should be to reduce N loss through denitrification, volatilization and leaching by either deep placement or split applications to match crop demand and to increase N-use efficiency. At the end of the rice season, the return to aerobic conditions sees rapid nitrification of newly formed and existing ammonium. Once the maize crop is established, split applications of N fertilizer can supplement mineralization of SOM to meet the N requirement of the crop without undue loss, even under irrigation. Water availability during the dry winter period varies among R-M systems and will determine yield of the maize crop and hence its N requirement. Achievement of efficient use by the system requires that the maize crop leave little mineral N at the end of the season because that may either depress N fixation by a legume crop such as mungbean, or will be rapidly lost during puddling for rice (Buresh and de Datta 1991).

Phosphorus management principles developed for R-W systems by Timsina and Connor (2001) are applicable to R-M systems as well. Phosphorus tends to accumulate in the soil due to fixation by Fe and Al, especially in acidic soils. Over time, large amounts of P can be fixed in that way (Kirk et al. 1990) while contributing slowly to available P pool of the soil. Phosphorus, however, solubilizes immediately after flooding, leading to a flush of available P (Kirk et al. 1990) increasing its supply to rice. Subsequent drying, however, reduces its availability to maize for which strong crop responses to P fertilizer are expected (Willet and Higgens 1978; Willet 1979; Sah and Mikkelsen 1989; Sah et al. 1989a,b). In systems of low P fertility, the repeated dry-wet transition in R-M system increases P extraction, further lowering fertility. Finally, management of P fertilizer for R-M systems must take account of residue and organic amendments.

The increased concentrations of Fe(II), Mn(II), and ammonium in flooded soils during rice cultivation displace K from the exchange complex into the soil solution (Ponnamperuma 1972). This displacement, however, ceases on return to aerobic conditions. Despite often having 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 flood plain Terai soils of Nepal and northern and eastern India, and soils of Bangladesh contain vermiculite, illite, or other K-fixing minerals (Dobermann et al. 1996, 1998). Improved K management may have great potential for improving the overall productivity of R-M systems of South Asia, but will require special consideration on soils containing K-fixing minerals. As with P, it may seem appropriate to make differential applications of K to component crops in R-M systems on non-K fixing soils, again with least K applied to rice with the aim of preventing loss by leaching.

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 considered (Dobermann et al. 1998) along with K inputs from sediments deposited from flood plains and flood water while formulating a rational K management strategy for R-M systems. 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, such as in Bangladesh, some K mining may be allowed by applying K below maintenance rate (Buresh et al. 2010). However, the extent of mining that could be allowed in a particular soil will require a complete understanding of the dynamics of K in the soil as well as the K input-output balance associated with the cropping system practiced.

Residue management

Soil puddling for rice with continuous soil submergence helps maintain SOM and sustain a supply of indigenous N originating from BNF and soil (Pampolino et al. 2008). The conversion from continuous rice cultivation with soil puddling and soil submergence to a R-M rotation with soil drying and tillage of aerated soil during land preparation for maize, however, can result in loss of SOM and soil fertility (Pampolino et al. 2010). Retention of crop residues after no or minimum tillage or on raised beds in R-W systems has increased yield and SOM in many experiments in South Asia (Humphreys and Roth 2008). In a 4-yrs experiment on a sandy loam soil in northern Bangladesh, SOM in surface soil layers of the permanent raised beds (PRB) had increased by 13–41% after 4 years (ie four rice+wheat+maize crop cycles) with straw retention (SR), with a greater increase with 100% recommended dose of fertilizers than 50% of the same. Soil organic C in PRB without SR was similar to the initial organic C prior to bed formation (Talukder et al 2008) which might be due to lesser biomass formation in absence of appropriate fertilization. We hypothesize that the establishment of maize after rice with reduced or no tillage and retention of crop residues could help conserve SOM and maintain soil fertility provided improved nutrient management is practiced. Reduced or no-till practices can also facilitate fast turnaround between crops. Experiments are underway in South Asia, particularly in India and Bangladesh, comparing maize and rice under conventional, reduced, and zero tillage in R-M systems to standardize nutrient management practices under differing tillage practices.

Bijay-Singh et al. (2008) made a simplified decision tree to illustrate guidelines for managing residues in rice-based cropping systems. They proposed that for the systems in which residue from rice or a non-flooded crop (such as maize) is retained or incorporated to ensuing rice, the management of residue depends upon whether soil during the recipient rice crop has been puddled. For non-puddled rice production, they recommended a no-till system in which the residues are left on the surface as mulch. For puddled rice production where crop residue cannot 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, will be required to compensate for nutrient removal in the residue. The removal of crop residue has the potential to reduce the detrimental environmental impacts arising with CH_4 emission from incorporating residue in flooded soils. For non-flooded rice or maize crop in rice-based system under reduced or no tillage, residue should be retained as mulch. Consistent residue removal for non-flooded crops with full tillage will result in loss of SOM and soil nutrient supplying capacity because of enhanced oxidation of SOM (Bijay-Singh et al. 2008).

Site-specific nutrient management in R-M systems

Existing fertilizer recommendations for rice and maize often consist of one predetermined rate of nutrients for vast areas of production. Such recommendations assume that the need of a crop for nutrients is constant over time and space. However, the growth and needs for supplemental nutrients of any crop can vary greatly among fields, seasons, and years as a result of differences in crop-growing conditions, crop and soil management, and climate. Hence, the management of nutrients for rice and maize requires an approach that enables adjustments in applying nutrients to accommodate the field-specific needs of the crop for supplemental nutrients. Site-specific nutrient management (SSNM), a plant-based approach, is used to address nutrient differences which exist within/between fields by making adjustments in nutrient application to match these location, or soil, differences. This approach for irrigated rice systems for Asia was developed in the 1990s by IRRI in collaboration with national partners across Asia (Fairhurst et al., 2007; Witt et al. 1999, 2007) to address serious limitations arising from blanket fertilizer recommendation for large areas, as practiced in Asia. It focused on managing field-specific spatial variation in indigenous N, P, and K supply, temporal variability in plant N status occurring within a growing season and medium-term changes in soil P and K supply resulting from actual nutrient balance. The plant-based SSNM strategies for rice is well advanced but that for maize is under development and evaluation. Here we present a few examples from Bangladesh and India where experiments on SSNM in R-M systems have been initiated.

An omission plot SSNM experiment on R-M system was conducted in Hyderabad, India, using rice hybrid PA6201 and maize hybrid MQPM1. The treatments included (1) control with no fertilizer- T1 (2) state recommendation- T2 (3) recommendation based on AICRP results- T3 (4) Full N, P, and K (SSNM)- T4 (5) N omission- T5 (6) P omission- T6 and (7) K omission- T7 (Table 7). The nutrient levels for T4 to T7 treatments were calculated based on the QUEFTS model (Jansen et al. 1990) taking into account organic carbon and available P and K in the soil as well as potential and targeted yields. Results from the experiment (Table 7) revealed that highest yields for both rice and maize and highest system productivity were obtained from the SSNM treatment (M. L. Jat, unpublished data). Omission of N from the optimum treatment reduced yield by about 1 and 3 t ha^{-1} in rice and maize, respectively. Yield loss in rice and maize (0.8 and 1.5 t ha^{-1}, respectively) was similar in P and K omission treatments. This suggests that N is by far the most limiting nutrient and greater response to applied nutrients is expected in maize than rice possibly due to a combined effect of higher yield potential in maize and change from puddled submergence condition in rice to a more aerobic ecology in maize.

Table 7 Grain yield (t ha^{-1}) of rice and maize, maize equivalent yield of rice, and rice-maize system productivity in an SSNM experiment (Source: ML Jat 2009, unpublished data)

Treatmenta	Rice yield (t ha^{-1})	Maize yield (t ha^{-1})	Maize equivalent yield (MEY) of rice (t ha^{-1})b	R-M system productivity in terms of MEY (t ha^{-1})
T1	4.11	3.87	3.88	7.76
T2	4.98	6.53	4.70	11.23
T3	5.01	7.04	4.73	11.77
T4	5.76	8.06	5.44	13.50
T5	4.88	4.86	4.61	9.47
T6	5.01	6.52	4.73	11.25
T7	5.00	6.65	4.72	11.37
CD(P=0.05) (kg ha^{-1})	232.1	715.7		

[a] Maize equivalent yield (MEY) of rice = [Grain yield of maize (t/ha)* selling price of maize (Rs/t) + (grain yield of rice (t/ha)* selling price of rice (Rs/t)]/selling price of maize (Rs/t)]; price of rice: Rs. 850 t^{-1}; price of maize: Rs. 900 t^{-1}

[b] T1 = control with no fertilizer; T2 = State recommendation; T3 = recommendation based on AICRP results; T4 = full N, P, and K; T5 = N omission; T6 = P omission; T7 = K omission

Table 8 shows data from another set of SSNM experiments, in maize from India. The trials were conducted in 2 major maize-based cropping systems, i.e.

maize-wheat at 8 locations (Delhi, Bajaura, Udhampur, Dholi, Ludhiana, Pantnagar, Banswara and Ranchi) and rice-maize at 3 locations (Jorhat, Banswara, Hyderabad) during Kharif 2008. Significantly higher yield of maize was recorded under SSNM compared to State recommendations at most of the locations. Omission plot yield data revealed differential indigenous nutrient supplying capacity of the study sites across locations (agro-ecologies). However, yield loss due to omission of N was higher as compared to P and K suggesting N as the major yield-limiting factor under all agro-ecologies. The response to applied nutrients varied from 1-5 t ha^{-1} for N to about 0.2-1.5 t ha^{-1} for P and K across locations. The results also suggest that response to applied nutrients must be included as a criteria to develop recommendations where nutrient application rates should be fixed based on expected response and application of maintenance rate, calculated on the basis of off-take of the concerned nutrient after a cropping season, might be a more economical approach under no or limited response scenarios.

Table 8 Effect of nutrient management practices on grain yield of maize (t ha^{-1}) at different locations in India (Source: ML Jat, unpublished data)

Nutrient management	Grain yield (t ha^{-1})							
	Delhi	Bajaura	Udhampur	Dholi	Ludhiana	Pantnagar	Banswara	Ranchi
State recommendation	7.78	5.69	4.06	3.65	6.76	4.44	5.93	3.69
SSNM	7.94	7.21	4.52	4.96	6.98	5.09	6.94	4.46
SSNM (-N)	4.46	2.76	2.26	3.21	5.87	3.11	1.72	2.78
SSNM (-P)	7.71	5.84	3.41	3.41	6.76	3.78	6.19	4.33
SSNM (-K)	7.36	5.87	4.41	3.69	7.33	5.22	6.41	3.89

Table 9 summarizes grain yield data from SSNM trials on rabi maize under R-M systems in two districts in NW Bangladesh. The experiment consisted of seven treatments namely, 1) N omission with ample P and K, 2) P omission with ample N and K, 3) K omission with ample N and P, 4) low P with ample N and K, 5) low K with ample N and P, 6) ample N, P, and K, and 7) ample N, P, K, S and Zn. Yields under all treatments differed in the two sites, with highest yields for ample N, P, and K and N, P, K, S, and Zn treatments. Yields in the minus nutrient treatments varied widely across farmers' fields within a district and also differed in the two districts, indicating large variations in the indigenous nutrient supplying capacities of the soils. Yields in minus N treatment were quite low but in low P and low K treatments were quite close to ample N, P, and K treatment indicating high response to added N but low response to added P and K due to low indigenous N but high indigenous P and K in the soils (Table 10). Yields in all treatments were generally higher in Rajshahi than Rangpur due to differences in soil nutrient levels.

Table 9 Grain yield (t ha^{-1}) of rabi maize in 10 farmers' fields in an SSNM experiment at two districts in NW Bangladesh in 2008-2009 (Source: J. Timsina, 2010, unpublished data)

Treatments	Rangpur	Rajshahi
N omission	0.5-5.1	3.4-3.9
P omission	3.9-8.3	4.5-8.5
K omission	4.1-8.1	5.3-7.9
Low P	5.5-8.8	6.2-8.9
Low K	5.8-9.8	6.5-8.6
NPK	6.0-10.3	6.7-10.3
NPKSZn	6.0-10.4	7.2-10.8

Table 10 Soil nutrient levels (ranges) in ten farmers' fields in two districts in NW Bangladesh (Source: J. Timsina, 2010, unpublished data)

Parameters	Rangpur	Rajshahi
pH	4.0-5.7	5.2-6.8
Total N (%)	0.02-0.08	0.04-0.075
Available P (ppm)	3-56	6-35
Available K (meq/100 ml)	0.38-0.64	0.1-0.38
Zn (µg ml^{-1})	0.2-1.7	0.2-0.57

Soil test methods: Total N, Kjeldahl; Avail. P, Bray-1; Avail. K, 1 N NH4-acetate; Zn, DTPA-extractable

The above results from India and Bangladesh highlight the highly variable response to applied N, P and K across agro-ecologies suggesting the necessity of SSNM to improve the productivity of R-M systems. Very high yield losses in maize in the N omission plots might be associated with the loss of SOM due to dry tillage in aerated soil after rice cultivation under submergence (Pampolino et al. 2010) and may need serious consideration for reduced or zero-till cultivation of maize with residue retained from the previous rice crop. However, there is a distinct knowledge gap in terms of nutrient dynamics and subsequent indigenous nutrient availability in R-M systems where no- or reduced tillage is practiced with or without the retention of residues of previous crop. We anticipate that soils under reduced tillage with retention of residues will differ considerably from the conventional tillage without retention of residues as far as nutrient dynamics is concerned and may need separate set of strategies in terms of nutrient application rate and timing.

Estimating fertilizer needs for R-M systems

Continuous production of high yielding maize may lead to the rapid depletion of mineral nutrients from soil unless appropriate nutrient inputs are supplied and best management followed. Maize hybrids grown in the rabi season in South Asia have an attainable grain yield of about 10-12 t ha^{-1}, with similar amount of non-grain biomass. To obtain such high yields, for example in Bangladesh, maize plants take up around 200 kg N, 30 kg P, 167 kg K and 42 kg S ha^{-1} (BARC 2005). Farmers, on the other hand, apply imbalanced fertilizers, with high amount of N and low amounts of P, K, S, and micronutrients. In 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. 2008, 2009). Nutrient depletion-replenishment studies in R-W systems have also shown negative balances for N and K and positive balance for P (Panaullah et al. 2006; Saleque et al. 2006; Timsina et al. 2006). Declining soil organic C, acid leaching of soils through CO_2-charged rainwater and consequent base (Ca, Mg) removal, and micronutrient deficiencies (e.g. Zn and B in calcareous and coarse-textured soils) may be associated with this (Ali et al. 2008, 2009). One recent estimate shows that about 200 kg ha^{-1} yr^{-1} N+P+K applied as fertilizers remain unutilized by the crops in these systems, mainly due to improper management practices such as imbalanced fertilizer doses, inappropriate time of fertilizer application, and inappropriate timing and amount of irrigation (BARC 2005).

Fertilizer N, P and K needs by crops, as determined with the SSNM approach, are directly related to Yat levels. It is thus important to know the Yat targets for crops when assessing probable opportunities for future crop production and the associated needs for fertilizers in intensive cropping systems such as emerging R-M systems. Buresh and Timsina (2008) illustrated how crop simulation models for rice and maize can be used to estimate attainable yield (Yat) targets with best crop management practices for Sadar Upazilla of Kushtia District in Bangladesh. In Sadar Upazilla, R-R and R-W were formerly the main cropping patterns. Starting in about 1990, maize was introduced during the *rabi* season to be grown after the harvest of rice. The area of maize production subsequently expanded rapidly and replaced *Boro* rice and wheat. The cultivation of *Boro* decreased by about 40-50% and wheat cultivation is now almost non-existent. Rice-rice and R-M are now the two predominant cropping systems. Based on interviews of farmers in January 2008 by the first author, the average yield of maize in this area is about 8 t ha^{-1}.

Buresh and Timsina (2008) used ORYZA 2000 and Hybrid-Maize to estimate climatic and genetic yield potential (Yp) of rice and maize using 20 years of satellite-derived historical weather data from NASA for Sadar Upazilla. Farmers generally transplant *Aman* rice from mid-July to mid-August and *Boro* rice from mid-January to mid-February. The Yp of rice was consequently determined for intermediate duration rice (about 110 to 130 days from seed to seed) with transplanting on 1 August for *Aman* and on 1 February for *Boro.* Farmers generally plant maize from November to mid-January. The Yp for maize was determined for a hybrid with duration of 1800 GDD and planting on 1 December. Simulation results showed that Yp for rice was higher for *Boro* than *Aman,* and Yp for maize was much higher than for rice (Table 11). Maize captured more solar radiation during the growing season and also experienced cool environment during the grain-filling period, resulting in high yield. The Yat for high financial return through use of best crop and nutrient management practices was set at 80% of the Yp (Witt et al. 2007). The Yat of maize established through this technique (11.1 t ha^{-1}; Table 11) was markedly higher than the currently reported average farmers' yield of 6 t ha^{-1}, indicating opportunities for future increases in maize yield through improved crop and nutrient management practices. Attainable annual yields were markedly higher for R-M (17.3 t ha^{-1}) than R-R cropping (14.1 t ha^{-1}) systems, suggesting much higher nutrient extraction and fertilizer needs for R-M than R-R as these cropping systems approach their Yt. The estimated yield can subsequently be used to assess evolving fertilizer needs as cropping system diversify, intensify and increase in yield.

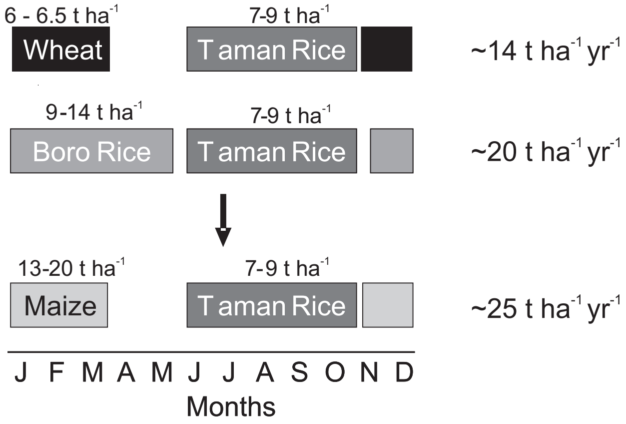
Table 11 Simulated Yp (t ha^{-1}) and growth duration (d) for rice and maize planted during farmers' preferred planting times in Sadar Upazilla, Kustia District, Bangladesh (Source: Buresh and Timsina 2008)

Season	Crop	Planting date	Yp (t ha^{-1})		80% of Yp (t ha^{-1})	Mean growth duration (d)
			Mean	Standard error		
Aman	Rice	1 August	7.7	0.2	6.2	110
Boro	Rice	1 February	9.9	0.1	7.9	121
Rabi	Maize	1 December	13.9	0.3	11.1	130

Likewise, Pasquin et al. (2007) demonstrated how diversification from R-R or R-W systems to R-M systems can impact on fertilizer use. They also used ORYZA 2000 and Hybrid-Maize and long-term satellite-derived NASA climate data to study the impact on fertilizer demand by changing from either R-R or R-W systems to R-M system in NW Bangladesh. The Yp of the *Aman* rice transplanted during the rainy season in June/July, is about 7-9 t ha^{-1}. When grown as a *Boro* crop towards the cooler months of the year, Yp increases but with associated risks of cold injury during the seedling stage. The Yp of maize is highest when planted during September to November (up to 20 t ha^{-1}), while wheat is ideally planted in

November achieving a Yp of about 6.5 t ha^{-1}. Figure 1 shows the production potential of R-W, R-R, and R-M systems. There is no alternative to growing rice in the rainy season so that the production potential changes depending on the second crop grown after T *aman* rice. The production potential is highest for R-M system with about 25 t grain ha^{-1} yr^{-1}, followed by R-R (20 t ha^{-1} yr^{-1}) and R-W systems (14 t ha^{-1} yr^{-1}).

Fig. 1 Potential grain production (t ha^{-1}) of rice-based cropping systems in Dinajpur, Bangladesh. (Source: Pasquin et al. 2007)



Site-specific nutrient management approaches developed for rice and maize have the potential to optimize nutrient management as farmers replace crops in their crop rotations. Fertilizer consumption is expected to increase when farmers shift from either a R-R or a R-W system to a R-M system due to a greater demand for nutrients at higher production levels. Shifting from one crop to another is likely to have moderate impact on fertilizer demand, while shifting from a single to a double or from a double to a triple-cropping system would result in increased fertilizer consumption and demand, as well as increased farmers' productivity (Pasquin et al. 2007).

Future priorities for research in nutrient management for R-M systems

As maize cropping becomes more widespread and intensive in South Asia an emerging issue of great importance is how to sustain the productivity of R-M cropping systems through integrated soil fertility management strategies. Recent anecdotal evidences of stagnation and declines in maize yield in R-M systems in Bangladesh appear to be related to soil fertility problems, including deficiencies of N, P, and K arising from improper N management and imbalanced/inadequate fertilizer use (Ali et. al. 2009). There is a need to understand more about the extent and rate of nutrient depletion and soil physical degradation in the intensifying R-M systems in South Asia before formulating appropriate amelioration strategies. To push the achieved grain yields even higher up the Yp curve will require larger amounts of nutrients, their better management and overall soil stewardship. On-farm nutrient management experiments with very high input and high-yielding maize crops is required to understand how to manage such systems to meet the requirement of maize in South Asia from a fixed soil resource base.

Nutrient management for the R-R and R-W systems has been widely researched and blanket fertilizer recommendations for these systems are somewhat available in South Asia. However, not much is known about soil and fertilizer management practices for the emerging R-M systems, particularly involving high-yielding maize hybrids. This system is complicated because the component crops are grown in sharply contrasting physical, chemical and biological environments as that for R-W systems (Timsina and Connor 2001). Here the role of SOM becomes crucial, as a supplier of secondary and micronutrients, and also, especially for maize, as a natural “soil amendment” that creates a congenial soil physical environment for these crops. Organic matter becomes more important given that most soils of South Asia currently have low organic matter contents. In this context, integrated plant nutrition system (IPNS), envisaging conjunctive use of inorganic and organic sources of nutrients, including crop residues, could be considered for sustaining soil health and crop productivity (Rao and Srivastava 2001). IPNS packages and management guidelines for intensive R-M cropping systems can be developed for use in follow-up technology dissemination initiatives for farmers in South Asia. Ali et al (2009) have suggested the following IPNS research for R-M systems for Bangladesh which can also be applied for other similar agro-ecological areas in South Asia:

1. Understanding soil fertility constraints in representative R-M growing areas across the country.
2. Assessing crop nutrient requirements for optimum yield targets for both maize and rice in the intensifying systems in the prevailing biophysical environments.
3. Multi-location research on mineral fertilizer use, possibilities of adding quick growing legumes such as mungbean into the system, making use of BNF in rice, use of appropriate bio-fertilizers for legumes, and crop residue retention and recycling techniques, etc.
4. Maximum use of residual fertility in the cropping system to reduce the cost of fertilizers.
5. Field testing the IPNS packages in comparison with farmers' existing practices.
6. Financial analysis of the IPNS packages to evaluate farmers' profit margins.
7. Farmers' feedback on the acceptance of IPNS packages

8. Combination of IPNS packages with water management and soil physical management, and with water-efficient maize that may be developed.

Large amounts of cow dung and poultry manure are produced in South Asia but during the dry season most is used as household fuel for cooking. Sharma and Biswas (2004) have presented the recommended IPNS packages for various cropping systems for different agro-climatic regions of India, but unfortunately little is mentioned about such packages for R-M systems. We suggest that future research address and generate the appropriate IPNS packages for R-M systems across different soil types and fertility levels in South Asia.

Research on SSNM for rice and maize separately has now been well developed and the SSNM technologies disseminated (Fairhurst et al. 2007; Witt et al. 1999, 2007). Future research and dissemination should now focus on SSNM for R-M systems considering the yield goals, crop demand for nutrients, indigenous soil nutrient levels, and residual soil fertility. Dissemination of nutrient management technologies for R-M systems will be faster if simple computer-based decision support systems (DSS) tools can be developed for use by farmers and extension workers from governmental and non-governmental organizations and from the private sector. One of such DSS is Nutrient Manager for Rice (IRRI 2009) that has already been developed, evaluated, and promoted in the Philippines and Indonesia and is under development and evaluation for India and Bangladesh. The partial maintenance and partial maintenance plus yield gain approaches presented by Buresh et al. (2010) for P and K can be used in Nutrient Manager for Rice, which is designed to quickly provide extension workers, crop advisors, or farmers with fertilizer best management practices for specific rice fields. This tool integrates the existing knowledge on SSNM in rice and is capable of providing field-specific N, P, and K recommendations based on farmer responses to about 10 questions (Buresh et al., 2010). Nutrient Manager for Maize (Witt et al. 2009) and for R-M systems for South Asia is in development and evaluation stage. Future approach should give priority to the development and refinements of such simple DSS tools for integration and widespread delivery of improved nutrient management strategies to diverse R-M agro-ecologies of South Asia.

Conclusions

R-M cropping systems are emerging in South Asia. Area under this system is much less compared to R-R, R-W or M-W systems but is increasing rapidly in recent years. The increase is very rapid in Bangladesh and South India. Yield potential of rice and maize is quite high in South Asia. However, large yield gaps between potential and attainable yields, between attainable and actual yields, and between potential and actual yields exist in farmers' fields. There is potential to reduce yield gaps through better crop and nutrient management despite the challenges and constraints in farmers' fields. This review has highlighted some of such constraints and challenges and also opportunities for better nutrient management for reducing yield gaps for R-M systems.

Nutrient demand of the R-M system is very high since high-yielding rice varieties and maize hybrids are used. High nutrient demand is associated with high extraction or uptake of nutrients from soils leading to declining fertility unless the extracted nutrients are replenished from external sources. This is particularly true for R-M systems where residues of both crops are generally removed from fields aggravating soil fertility depletion, especially K. However, nutrient balance studies in R-M systems are very few in South Asia. Recently some efforts are being made in India and Bangladesh to develop nutrient balances for these systems but conclusive results are not yet available. SSNM provides scientific principles for optimally supplying crops with nutrients as and when needed for specific fields in a particular cropping season. Application of SSNM principles, aided by nutrient balance studies, can help improve nutrient management in R-M systems towards improving yield and profitability. This will, however, require better understanding and development of SSNM principles for maize to the extent of rice.

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Role of industry initiatives in extension activities in India

G Raviprasad • Madhab Adhikari

Abstract Extension builds the bridge between lab and land. There are different agencies available in India, who are today helping new technologies to reach the end-customer. They carry out extension activities as per their organizational mandate. In this paper specific methodologies are discussed which are used by the industry in agri-input sector to take the new technologies and products to the farming community. The methods include individual, group and mass media to reach the end customers. It also includes number of technology interventions and training methods, which can be used to increase the effectiveness of industry led extension activities.

Keywords Extension activities • agriculture • industry

Introduction

Agricultural extension was once known as the application of scientific research and new knowledge to agricultural practices through farmer education. The field of extension now encompasses a wider range of communication and learning activities organised for rural people by professionals from different disciplines, including agriculture, agricultural marketing, health, and business studies.

The term, 'extension' was first used to describe adult education programmes in England in the second half of the 19th century. These programmes helped to expand - or extend - the work of universities beyond the campus and into the neighboring community. The term was later adopted in the United States of America, while in Britain it was replaced with "advisory service" in the 20th century.

In the US, an extension agent is a university employee who develops and delivers educational programs to assist people in economic and community development, leadership, family issues, agriculture and environment. Another

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program area extension agents provide is 4-H and Youth. Many extension agents work for cooperative extension service programs at land-grant universities. They are sometimes referred to as county agents or educators.

The latest definitions of extension show some interesting trends how the discipline has developed over the years. The essence of agricultural extension is to facilitate interplay and nurture synergies within a total information system involving agricultural research, agricultural education and a vast complex of information-providing businesses (Neuchatel Group 1999). Extension [is] a series of embedded communicative interventions that are meant, among others, to develop and/or induce innovations which supposedly help to resolve (usually multi-actor) problematic situations (Leeuwisand van den Ban 2004).

The agencies involved in extension activities in India

Government Agencies: State department of agriculture; Krishi Vigyan Kendras (KVKs); Agricultural Research Institutes of ICAR; NGOs; and Agri. Input Companies

Four paradigms of agricultural extension

Any particular extension system can be described both in terms of both how communication takes place and why it takes place. It is not the case that paternalistic systems are always persuasive, nor is it the case that participatory projects are necessarily educational. Instead there are four possible combinations, each of which represents a different extension paradigm (NAFES 2005), as follows:

Technology Transfer (persuasive and paternalistic);
Advisory work (persuasive and participatory);
Human Resource Development, and
Facilitation for empowerment (educational and participatory).

The mandate of industry

Industry today touches all the facets of the above four paradigms of agricultural extension in some way or other. The mandate of Industry in context with agricultural extension is as follows:

Brand building;
Introduction of new product;
Introduction of new technology/concept;
Developing awareness of latest products/molecules;
Providing solutions for better production and better protection;
Creating awareness for integrated nutrient management and integrated pest management, and
Differentiating its product vis-a-vis competitors.

Why industry should participate in extension activities

Today all the three wings need to participate in extension activity but industry is playing an increasing role due to number of reason. The Government wing is suffering from lack of manpower and infrastructure. Maximum time is being spent on administration than on extension. NGOs mostly engaged in socio-economic developmental segment and lack of coordination due to presence of too many agencies and accountability issues has started creeping in. Agri-input Industry's immediate concern is higher sale of its own brand. But since most of the new technologies come through industry it is mandatory for them to develop the concept, which in turn helps the farming community.

Different extension approaches taken by industry

The following methods are used by the industry as a whole and in most of the cases a combination of activities are used as extension is always a holistic approach not a singular activity done one fine morning. The popular methods are Individual Contact, Farmer meeting, Crop Seminar, Result Demonstration, Soil testing, Local Talent, Exhibition, Farmer mailers, Farmer testimonials, Radio and Television Programmes, Radio and TV commercials, News paper articles, News paper advertisements, Hoarding and Agricultural fairs.

Individual Contact

Individual company representatives meet the farmers at their home/farm and explain them about new technologies and products. This is the best method for rural marketing as far as adoption rate is concerned. The tools used are leaflets, product brochure, crop kits, detailing chart. The advantages of this are that the success rate is very high as you spend a lot of time enforcing the communication. The cost for this activity is very high. The availability of qualified manpower and high attrition rate across companies is the major constraint.

Farmer Meeting, discussion forum

Organising a group meeting for farmers at their village in some common area like choupal/village temple etc. This is another very successful method of technology dissemination. The tools used are leaflets, product brochure, Multimedia, film shows etc.The advantages of this are that many farmers can be educated at a given point of time. Two companies with complementary products can do it jointly. The cost depends on the number of participants but definitely cheaper than individual contact. The major constrain is that you need a qualified person for organizing such events who can answer questions covering all aspects of agriculture.

Crop Seminar

Organising a technical meeting for farmers in collaboration with scientists at a research station or good location. This is another very successful method of technology dissemination. The advantages is that many farmers can be educated at a given point of time. Scientists can add real value in participating in this kind of programmes. The cost depends on the number of participants but definitely cheaper than individual contact.

Farmers' testimonials

Using farmers testimonials in meetings and in mailers is a good method of extension where the farmers share the benefits of the technology with his peers. The main advantages is that it has got a good impact as the news spreads very fast and farmers believe what their peers say. The cost of mailers is very cheap. The constraints are due to the facts that you need a have a good farmer's data base.

Result demonstration, Harvest days

Organizing a result demonstration in a prominent and easy to access farmers' field with a control plot and show the farmers the benefits of new technology. The farmers are normally taken to the plot at different stages and shown the benefits. Concluded by a harvest day. The advantages is that many farmers can be educated at a given point of time. Seeing is believing. The cost depends on the plot size and number of farmers taken to the plot. The constraint is due to the fact that it is difficult to monitor the farmers field on a regular basis and the results are dependent on many uncontrolled factors

Mass campaign through decorated vans

Normally a decorated jeep or van is taken through the villages and a combination of individual contact and farmers meeting are used. The advantages is that many farmers can be educated at a given point of time and easy to get attention of the farmers. The cost is high. Logistics is the most critical issue to handle and the process requires number of permission from competent authorities.

Soil testing/leaf analysis at Laboratory

Soil sample/leaf sample can be collected from the farmers' field and send to company lab or any other designated labs. The advantages is that many numbers of tests can be done in a year and result can be given in 15 days with good IT support system. Along with NPKS, EC, pH, organic carbon, and micronutrients can also be tested. The cost to company is high. Normally micronutrients and leaf analysis are done with some minimum fees from the farmers as the cost is very high. The sample should reach the plant in proper condition with appropriate marking.

Soil testing through kits

A handy kit carried is by the company representative and soil testing can be done at the farmers field in half an hour. It has the advantages that around 20 tests can be done in a day by a person and the result can be given there itself. The kit can be used for pH, EC, Sulphur and Organic carbon. Its cost is less compared to other forms of testing . However the most of the tests are qualitative in nature.

Mobile Soil testing Van

A mobile van with soil testing kits goes to selected areas and organizes soil testing camps there. The advantage is that around 50 tests can be done in a day and the result can be given there itself. The van can conduct NPKS, EC, pH and Organic carbon tests. The cost to company is high. The logistics is the most critical issue to handle and requires a dedicated soil testing specialist.

Farmers call centre

A toll free number where farmers can call about their agricultural problems and get a solution through a panel of agricultural experts. The farmers can call at their own time and the company can get valuable farmer data base. The cost to company is high. Sometimes solution to pest or disease related issues can not be solved over phone. Normally the company representative needs to visit the farmer for a follow-up.

Farmers' event

The company can organize an event or take part in an existing event. Normally knowledge dissemination happens through leaflets and small group meetings along with the event. The participation and enthusiasm level is very high among farmers. The cost to company is medium. It is difficult to have very serious meeting along with the same. But an excellent brand building tool.

Local talent/Puppet Show

Daskathia, Burakatha, Puppet show, Kirtan are the different forms of local talent programmes where local artists perform on the stage on some mythological stories. They also build up a story based on the message you want to convey. Excellent participation and the message goes right into the mind of the farmers as they relate to it quickly. The cost to company is high. However, if the message is not clear it will have only entertainment value.

Newspaper article

Newspaper articles with technical issues or product is a good way of spreading your message. It has very high reach and farmers trust the words in newsprint. The cost to company is high. However, if used only for product publicity it is treated as a propaganda by the company.

Exhibition

Farmers fair and traditional fairs are a good medium to participate. You need to have a good stall with multimedia and few agricultural experts to solve farmers issues. The footfall to your stall will be high and with some qualified experts you can very well spread the technology. The cost to company is high. The constraint is that all persons visiting the stall may not be farmers.

Channel training

Technical training programme is organised for dealers and retailers where detailed technical session is conducted along with commercial sessions. The channel members are the persons who are in touch with the farmers. Proper training for them helps in better technology dissemination. The cost to company is high. The main point for consideration is that you should select participants carefully for a better learning experience.

Training of extension personnel

Technical programme for extension personnel like sugarcane officers, officers of state department of agricultures, Village Level Workers (VLWs) is a good tool in informing them about new technologies. It is a good public private partnership model where both the agencies can learn from each other and work out ways to reach the farmers.

Mass Media-TV, Cable TV, Cinema, Radio, Newspaper

Mass media can be used in various forms like participation in agricultural programmes in TV and Radio. The medium is mostly used for brand building exercise. It has a high reach. The cost to company is high. You get limited exposure where the message should be concise as the cost is high. You need to choose the state based on media reach

What Industry has done in India

Products like DAP, 28-28-0, MOP, Urea are in fact popularized by industry only through its strong extension work. Brands like Gromor, Godavari, Nagarjuna, Paras are household names for farmers today. The concept of sulphur fertilisation is developed in India by Coromandal and its flagship brand Gromor Sulphur is used by more than 3 million farmers. The concept of water soluble fertilisers was started in India by Nagarjuna Fertilisers and today with the entry of Coromandal with its strong extension network, the technology has grown manifold to the benefit of India farmers. All new molecules of pesticides are developed by industry only, thereby giving farmers the most important tool for plant protection. Bt cotton seed has been popularized in India by Industry. Indian implements industry has taught farmers the use of tractors and other advanced implements. In short industry is the source of new technologies today and thus the onus is on the industry to disseminate the same to the farmer for the benefit of Indian Agriculture

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Research on potassium in agriculture: Needs and prospects

Volker Römheld • Ernest A Kirkby

Abstract This review highlights future needs for research on potassium (K) in agriculture. Current basic knowledge of K in soils and plant physiology and nutrition is discussed which is followed by sections dealing specifically with future needs for basic and applied research on K in soils, plants, crop nutrition and human and animal nutrition. The section on soils is devoted mainly to the concept of K availability. The current almost universal use of exchangeable K measurements obtained by chemical extraction of dried soil for making fertilizer recommendations is questioned in view of other dominant controlling factors which influence acquisition K from soils by plants. The need to take account of the living root, which determines spatial K availability is emphasized. Modeling of K acquisition by field crops is discussed. The part played by K in most plant physiological processes is now well understood including the important role of K in retranslocation of photoassimilates needed for good crop quality. However, basic research is still needed to establish the role of K from molecular level to field management in plant stress situations in which K either acts alone or in combination with specific micronutrients. The emerging role of K in a number of biotic and abiotic stress situations is discussed including those of diseases and pests, frost, heat/drought, and salinity. Breeding crops which are highly efficient in uptake and internal use of K can be counterproductive because of the high demand for K needed to mitigate stress situations in farmers' fields. The same is true for the need of high K contents in human and animal diets where a high K/Na ratio is desirable. The application of these research findings to practical agriculture is of great importance. The very rapid progress which is being made in elucidating the role of K particularly in relation to stress signaling by use of modern molecular biological approaches is indicative of the need for more interaction between molecular biologists and agronomists for the benefit of agricultural practice. The

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huge existing body of scientific knowledge of practical value of K in soils and plants presents a major challenge to improving the dissemination of this information on a global scale for use of farmers. To meet this challenge closer cooperation between scientists, the agrochemical industry, extension services and farmers is essential.

Keywords Potassium availability • potassium micronutrient interaction • spatial availability of potassium • K/Mg ratio • abiotic stresses • biotic stresses • drought resistance • frost resistance • food quality • K/Cd relations

Introduction

Large areas of the agricultural land of the world are deficient in potassium which include 3/4 of the paddy soils of China and 2/3 of the wheat belt of Southern Australia. Additionally export of agricultural products and leaching of K particularly in sandy soils contributes to lowering soil K content (Rengel and Damon 2008). Soils on which potassium deficiency occurs vary widely and include acidic sandy soils, waterlogged soils and saline soils (Mengel and Kirkby 2001).

At two recent conferences held in India, the first in Ludhiana (Punjab) (IPI-PAU Intern. Symposium 2006), and the second in Bhubanaswar (Orissa) (IPI-OUAT-IPNI Intern. Symposium 2009) at both of which crop nutrition was discussed, attention was drawn to the stagnation and even progressive decline in crop yields in the Indian sub continent as a consequence of interruption of soil recycling of organic matter and mineral nutrients, especially potassium (K). In India animal dung (as manure cakes) and crop residues are used as a source of bioenergy for cooking and heating without recycling the K rich ash or sludge back to farming land which receives only low, if any, input of K fertilizers (Hasan 2002). As a consequence, a progressive decline in soil fertility including organic matter and K status is to be expected as an important factor in restricting crop yields.

This problem is not only restricted to India, it is a worldwide one. According to Smil (1999), more than half the dry matter in the global harvest is in the straw of cereal and legume crops and in the tops, stalks, leaves and shoots of tuber, oil, sugar and vegetable crops. This global bulk of dry matter which contains nutrients and is taken away at harvest and utilized for other purposes (e.g. heating, animal feed, biofuels), means that large amounts of nutrients are removed from the soil. Globally, the annual above ground parts of crops (phytomass), contains 75, 14 and 60 million tonnes of nitrogen (N), phosphorus (P) and potassium (K), respectively. However, whereas nutrient applications of N and P are at similar levels to total nutrient content in crop phytomass removal (80 and 14 million tonnes, respectively), K is applied at a much lower level, to replenish only 35% of the K removed (Smil, 1999), a figure which is likely to be much lower in developing countries.

The consequence of a lack of adequate nutrient recycling leading to a loss of soil structure and decline in soil fertility was appreciated long ago by the renowned German agricultural chemist Justus von Liebig and discussed in the 9th edition (1876) of his well - know text book "Chemistry in its application to agriculture and physiology". Justus von Liebig recognised that K as one of the major plant nutrients played a key role in soil fertility and he developed K mineral fertilizers, so called "patent fertilizers", to increase crop yields. These findings are as relevant today as they were then. The current move towards using crop residues or even entire crops as biofuels, in order to place less dependence on fossil fuels in developed and developing countries such as the USA or China, will also in the long-term lead to a decline in soil fertility.

Taking a more holistic view, there is a need to consider progressive crop yield decline not only in terms of inadequate recycling of organic matter and mineral nutrients, but also in relation to annual flooding problems in India. The benefits of organic matter in soil acting as a physical barrier to a run-off of rain water can not be ignored. Also the lower infiltration of rain water on agriculturally degraded land poor in soil structure promotes the regular flooding of river deltas during the Monsoon period (Hermann et al. 1994). It also brings about topsoil runoff and erosion which is evident not only in India but occurs worldwide. Yoshida (2001) estimated an economic value of 68.8 billion USD for the multifunctional detrimental role of agriculture in Japan on the landscape and the environment including runoff and erosion.

Another consequence of decline in soil fertility in agricultural land is the greater prevalence of sustained periods of drought resulting from poorer water storage throughout the soil profile. These increasing events of drought and other abiotic stresses (e.g.heat) arising from loss of soil fertility as well as from global warming will necessitate a specifically high supply of K for stress mitigation (see below). The inadequate recycling of K in Indian agriculture thus puts these soils and the crops they carry at risk. In Germany too, farmers often respond irrationally to drought events by decreasing rates of K fertilization (Joachim Rauch 2007 pers. comm.).

In this paper we consider various aspects relating to K use in crop production. This includes not only the supply of K from the soil to crop plants but also the role of K in animal and human nutrition. Attention is drawn to the great need for more effective transfer of information to the benefit of the farmer from the vast amount of knowledge which has already been accumulated on K in soils and plants. We critically discuss some of the more recent research work on K in soils and plants included in various papers presented at the Potassium Conference at Orissa (IPI-OUAT-IPNI Intern Symposium, 2009). We also address areas of new and developing interest in K in soils and plants and discuss current interests in the important role of K in protecting crops from abiotic and biotic stresses and consider areas in which basic and applied research might be carried out suggesting means by which farmers might benefit more from research findings.

Need for knowledge dissemination

On a global scale there is an enormous gap between agricultural scientific knowledge and its dissemination and application to farming practice, particularly in developing countries. This point was made very forcibly by Krauss (2003a), the then Director of the International Potash Institute, when in discussing the work of the Institute in retrospect and prospect, he wrote, "Much of the immediate future challenge is for knowledge transfer, particularly to poor farmers and their advisors and extension workers. Balanced K fertilization and avoidance of K mining, (K applied by fertilizers less than that K removed by crop harvest), will prevent farmers from falling into the poverty trap and will help them leave the vicious circle of declining soil fertility".

This urgent need for dissemination of scientific knowledge was made very clear during two recent horticultural visits, one to China and the other to Italy. In the intensive tomato production area of Shandong province in China, severe Mg deficiency symptoms were visible on many of the plants. These symptoms were typical of what might be expected from too high a K supply (high K-induced Mg deficiency, Römheld and Kirkby 2007), which was confirmed later by soil and plant analyses. The extremely high K content in the soils of these Chinese glasshouses near Shouguang in Shandong had depressed Mg uptake, inducing low Mg leaf concentrations (Heenan and Campbell 1981; Seggewiss and Jungk 1988). Neither the local farmers nor even the scientific advisors were aware that these symptoms of intercostal chlorosis of the leaves adjacent to the fruit trusses, were caused by lack of Mg. In western Europe and the USA too, Mg deficiency symptoms in some horticultural and agricultural crops can be widely observed during reproductive growth stages (Römheld and Kirkby 2007).

Another example of an inappropriate recommendation for K fertilizer use, again arising because of lack of understanding of interactions between Mg and K in plant nutrition and the practical benefits of soil and plant analysis, was recently demonstrated in two nearby kiwi (*Actinidia deliciosa*) orchards near Bologna in Italy. In one of the orchards ("Gurini"), Mg deficiency symptoms similar to those described above for tomato were clearly recognisable, whereas in the other ("Dalle"), the plants were showing symptoms of necrosis of the leaf margins clearly indicative of K deficiency. The visual diagnoses in both orchards (Francesco Penazzi 2009 pers. comm.) were confirmed by soil and leaf analyses which are shown in Table 1. The inappropriate use of K fertilizer recommendations in these kiwi orchards strongly supports Krauss`s view that "ignorance of soil tests prevents the application of balanced fertilization in the adequate use of potash" (Krauss 2003a).

Table 1 Visual symptoms and results of analysis of soil (0-60 cm) and corresponding leaf samples of two kiwi (*Actinidia deliciosa*) orchards near Bologna, Italy

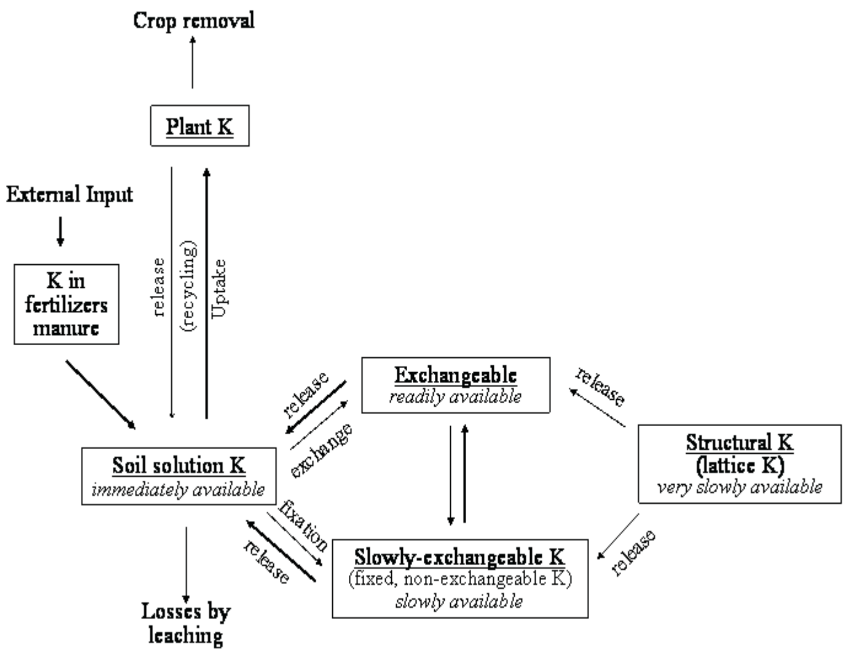
Kiwi orchard	Visual symptoms (June 2009)	Classification by soil analysis	Leaf analysis (% in leaf DM)
"Gurini" (sandy soil)	Mg deficiency	K: high-very high Mg: low-very low	K: 1.49 (adequate) Mg: 0.43 (low)
"Dalle" (clay loam soil)	K deficiency	K: very low Mg: very high	K: 0.80 (low) Mg: 0.67 (high)

Ensuring that appropriate scientific knowledge is passed on to farmers and growers is still a great challenge in agriculture and horticulture. The means of achieving this challenge for the benefit of farmers and growers are considered in more detail in relation to research developments in "Need for future research on potassium" and "Summary and prospects".

Potassium in soils: present knowledge

The present conceptual understanding of soil K availability is the existence of four distinct K pools differing in accessibility to plant roots with reversible transfer of K between the pools (Syers 2003). This concept is illustrated in Fig. 1 which presents an up to date version of the K cycle in soils (see also Öborn et al. 2005). Soil solution plays a pivotal role in providing the pathway for K uptake from the soil to plant roots. Although this pool is very low in K content, representing only about 5% of total crop demand at any given time (McLean and Watson 1985), or 0.1 - 0.2 % of the total soil K, it is immediately available and replenished by both the exchangeable K (EK, readily plant available K) and the slowly or non-exchangeable K (SEK, slowly plant available K) pools. These two pools, EK and SEK make up about 1-2% and 1-10% of the total K respectively and are the main contributors to K uptake by plants. The exchangeable fraction (EK) i.e. the K held on negatively charged sites of clay minerals and soil organic matter, is in rapid equilibrium with soil solution K and is considered to be readily available to plants. Its measurement, as discussed below, can often, but not always, provide a useful indicator of K soil status in relation to plant supply. Potassium is released from the slowly or non-exchangeable K pool (SEK) from lattice wedge sites of weathered micaceous clay minerals which are selective for K ions (see Mengel and Kirkby 2001). The remaining pool which holds the bulk of K (90-98% of the total soil K), is held in structure of the primary K bearing minerals, such as micas and feldspars being released very slowly by weathering to replenish the EK and SEK pools as indicated in the figure. Most of the total soil K available to plants is usually located in the topsoil.

Fig.1 Potassium cycle in soils (after Syers 2003)



These different K pools are not only of relevance to K acquisition by plants but also to K leaching through the soil profile as evident in Fig. 1. In sandy soils as well as in acid lateritic soils containing kaolinitic clay minerals low in CEC, rates of K leaching can be very high so that considerable amounts of K can be lost (Table 2, Wulff et al.1998) (Sharpley 1990). On such soils where high rainfall conditions prevail, split application of K fertilizers during the growth period has proved beneficial, simultaneously lowering loss of K by leaching and raising efficiency of use of the K fertilizers applied (Kolar and Grewal 1994).

Table 2 Average rate of K leaching in a sandy soil during the winter seasons 1989/1990 until 1994/1995 as affected by the annual rate of K fertilization (Wulff et al. 1998

K fertilization rate (kg K ha^{-1}a^{-1})	K leaching (kg K ha^{-1}a^{-1})
0	22
60	42
120	79
180	133

The most usual method used worldwide to assess the K status of a soil for the likelihood of obtaining a response in crop yield to fertilizer additions is the measurement of exchangeable K. This determination is made by extracting EK from air dried topsoil by one of a number of various well accepted chemical extractants which include NH$_4$OAc, NH$_4$Cl, CaCl$_2$, Mehlich No 1 and 2, the choice depending mainly on local usage and tradition. Differences between the extractants are only marginal in sensitivity (McLean and Watson 1985). The relationship between the amounts of exchangeable K and crop yield can be extremely close as reported for example by Johnston et al.(1998) for grain yields of winter wheat and yields of field beans (Vicia faba L.) grown on a silty clay loam soil at Rothamsted in the UK. However, as discussed by Syers (2003) much of the reported information in the UK relates to single soils or a narrow range of soils which may have led to an overemphasis on the usefulness of EK.

There is abundant evidence of the importance of SEK in soils and its availability to plants (Syers 2003). For example Mengel et al. (1998) were able to show that silt in loess derived soils which is high in 2:1 layer silicates interlayer K is able to provide large quantities of SEK to ryegrass. It is for this reason that Kuhlmann and Wehrmann (1984) found no response to K in grain yield of cereals growing on these loess soils even at very high levels of K application. Also different methods of soil analysis for available K showed no relationship to K fertilizer requirement. In India, Prasad (2009) has recently suggested that EK values are inadequate for fertilizer recommendations because of the contributions of non-exchangeable (SEK) and subsoil K to uptake. Kuhlmann and Barraclough (1987) reported that winter wheat could acquire 50% of its K from the subsoil. Certainly although EK is used widely as a measure to determine soil K availability and predict K fertilization needs of crops, its suitability and reliability is unsatisfactory in soils that contain 2:1 layer silicates and have the ability to retain K as is the case of flooded soils used for rice production (Dobermann et al. 1996).

Plant available K can be affected by long-term changes in total K in the soil. A simple calculation shows that in soils with a low total K content as in sandy soils, rapid K depletion can occur over relatively short periods if K removal is not balanced by regular K fertilization with mineral fertilizers or by adequate recycling of crop residues and organic manures or both (Table 3).

On this sandy soil, low in K, with an annual negative balance of 40 kg K ha^{-1}, only 44 years are required to remove 25% of the stock soil K. This so-called “potassium mining” is common. According to Hasan (2002), 72% of India`s agricultural area representing 266 districts are in immediate need of K fertilization. Such imbalances in K are widespread in agriculture and can also be

Table 3 Length of time required for 25% depletion of K from a topsoil with a high or low total K content and a low or high negative K balance sheet (the two model calculations show normal and worst case scenarios).

K content in top soils: 0.1 - 3.3% = 7 000 - 228 000 kg K ha^{-1}

Required years for assumed depletion of 25%

Normal scenario:

Balance - 5kg K ha^{-1} a^{-1} Top soil 3.3% K

$$\frac{228\ 800 \cdot 25}{5 \cdot 100} = 11\ 400 \text{ years (e.g. clay soil)}$$

Worst case scenario:

Balance - 40kg K ha^{-1} a^{-1} Top soil 0.1% K

$$\frac{7\ 000 \cdot 25}{40 \cdot 100} = 44 \text{ years (e.g. sandy soil)}$$

found in western states of Canada (Table 4). In contrast to K, the ratio of fertilizer use to that removed by harvest for N and P is usually much higher. Imbalance between K and N is often exacerbated by the sole application or overuse of N fertilizer, a fact which needs to be stressed in agricultural practice.

Table 4 Potassium removal by crop harvest and application by fertilizer (M kg per Province) and the ratio (fertilizer use: removal by harvest) compiled for 3 provinces of West Canada in 1996.

Province	Potassium		
	Removal by harvest	Fertilizer use	Ratio (%)
Manitoba	331	92	28
Saskatchewan	640	59	9
Alberta	601	128	21

On organic farms where the use of mineral fertilizers is strongly restricted, soil K status should be carefully monitored. Not only has the immediate K requirement for crop growth, including its beneficial effects on biotic and abiotic stresses to be taken into account (see below "plant aspects") but additionally the long-term K balance in the soil. As shown by Mayer (1997), (Table 5), for an organically managed farm in south Germany, a loss of 7 kg K ha^{-1} yard gate balance between input and output over a one year period ensued which appears quite reasonable. In the field balance over the same year of investigation, however, there was an extremely high internal loss which was more than five-fold greater at 36 kg K/ha representing an annual loss of almost 1 metric ton of K from the farm i.e., (1195 – 239 = 966) kg K. This internal loss of K was traced back to K leaching during rainfall from manure heaps which had been temporarily deposited on the field margins (Mayer 1997). Interestingly, drought-induced K deficiency symptoms in non-grasses such as legumes were observed on this organic farm.

Table 5 Potassium balance sheets for an organically managed farm (33.5ha) at Stuttgart –Ruit, Germany measured at a farm level (yard gate balance) and at a field level (field balance) for 1993/1994 (Mayer1997).

	Yard gate balance		Field balance	
	kg a^{-1}	kg ha^{-1} a^{-1}	kg a^{-1}	kg ha^{-1} a^{-1}
Inputs	233	7	3910	117
Outputs	472	14	5105	152
Balance	-239*	- 7	- 1195*	- 36

● Internal farm K losses: 1195 - 239 = 956 kg K a^{-1}

Potassium in plants: Present knowledge

Potassium (K) is the most abundant inorganic cation in plant tissues. In adequately supplied plants it may make up about 6% of the dry matter or concentrations of about 200 mM (Leigh and Wyn Jones 1984). K is unique as a plant nutrient as it occurs exclusively in the form of the free ion. Under K deficiency cytosolic K activity is maintained at the expense of vacuolar K activity (Leigh 2001). Highest concentrations of K are found in young developing tissues and reproductive organs indicative of its high activity in cell metabolism and growth. K activates numerous enzymes including those involving energy metabolism, protein synthesis, and solute transport (Mengel and Kirkby 2001; Amtmann et al. 2008). In cells K is needed in the maintenance of transmembrane voltage gradients for cytoplasmic pH homeostasis and in the transport of inorganic anions and metabolites (see White and Karley 2010). In long distance transport, K is the dominant cation within the xylem and phloem saps neutralizing inorganic and organic anions, conferring high K mobility throughout the entire plant (Jeschke et al. 1997). Uptake and accumulation of K by plant cells is the primary driving force for their osmotic expansion (Mengel and Kirkby 2001).

The basic biochemical and physiological functions of K have been described in detail in the main textbooks in plant nutrition (Marschner 1995; Mengel and Kirkby 2001; Epstein and Bloom 2005). Processes described considered include osmoregulation and cell extension, stomatal movement, activation of enzymes, protein synthesis, photosynthesis, phloem loading and transport and uptake. Uptake of K by root cells from soil solution is a highly efficient process and not usually limiting to K uptake. Even when K is in short supply the expression of genes encoding high-affinity K$^+$ influx systems increases (Shin and Schachtman

2004). More recent findings and research developments concerning the role of K in biotic and abiotic stress mitigation in plants in relation to agricultural practice are discussed in "need for future research on potassium".

Mild K deficiency in crops does not immediately result in visible symptoms because of the high rate of redistribution between mature and developing tissues. At first there is only a reduction in growth rate (hidden hunger) and only later do chlorosis and necrosis begin in the more mature leaves. In many crop species including maize and fruit trees these symptoms begin in the margins and tips of the leaves but in others including some legumes irregularly distributed spots occur on the leaves (Mengel and Kirkby 2001). Plants suffering from K deficiency show decrease in turgor and become flaccid under water stress particularly during the midday period. Plant roots sense or signal changes that occur after the onset of K deficiency but no major changes take place in biomass partitioning or root architecture as occurs under N and P deficiency. Arabidopsis roots respond to K deficiency by upregulation of high affinity K influx systems as mentioned above, and the production of reactive oxygen species (ROS) and ethylene, ROS being accumulated in discrete regions of the root that have been active in K$^+$ uptake and translocation (Shin and Schachtman 2004).

In field crop nutrition, two of the most recognized roles of K are in photosynthesis and the maintenance of cell turgor in plants. Applying drought stress to wheat plants at three levels of K supply at sub - optimal, optimal and supra - optimal rates, photosynthesis was shown to decrease under drought stress but the effect was alleviated by the increased rate of K supply (Table 6) (Sen Gupta et al. 1989). Supply at 2mM K supported maximal photosynthesis in well watered plants but not under drought stress whereas at the supra - optimal level of 6mM K the effect of the drought stress was much less severe. The practical significance of this finding is the well-known greater need for K by crops that are subjected to drought stress. The primary effect of the higher K treatment was in maintaining the stromal K concentration of the chloroplasts to allow CO$_2$ fixation. Under K deficient conditions photosynthesis is depressed as a consequence of sucrose accumulation in the leaves and its effect on gene expression (Hermans et al. 2006). Depression of photosynthesis causes an excessive accumulation of light energy and photoreductants in the chloroplasts which in turn leads to activation of molecular oxygen, the formation of reactive oxygen species (ROS) and chloroplast damage (Cakmak 2005).

Table 6 Effect of K$^+$ supply (mM) to wheat plants grown in a sand/peat mixture on photosynthesis of leaves at declining leaf water potentials (increasing drought stress) (Sen Gupta et al. 1989)

K$^+$ supply (mM)	Photosynthesis (µmol CO$_2$ m^{-2} s^{-1})			
	Leaf water potential (-MP$_a$)			
	1.1	1.5	2.0	2.5
6.0	35	35	32	24
2.0	35	33	23	15
0.2	29	15	6	n.d.

The importance of K as an osmoticum in maintaining turgor in crops is particularly evident from N/K interaction studies in field grown crops (Milford and Johnston 2007). A major determinant of growth and prerequisite for high yields in most arable crops is the rapid expansion of the leaf canopy in the spring for the efficient capture of CO$_2$ by photosynthesis and its conversion to sugars and dry matter. Nitrogen is the major driver of leaf canopy expansion which is achieved by increase in cell division and cell expansion i.e. cell number and cell volume, which also necessitates a corresponding uptake of K in the leaf tissues to maintain turgor. In field experiments as much as 10-15 t ha^{-1} more water was present in the shoots of cereals well supplied with N as compared with those that were not. For sugar beet the amount was even greater with crops well supplied with N having 30-35t ha^{-1} more water than those with limited N supply. This increase in hydration was expressed by the presence of enhanced quantities of osmotic solutes in the cell vacuoles, particularly K to maintain adequate turgor for continued cell expansion and growth, in accordance with a higher K uptake.

In agreement with the classic experiments of Leigh and Johnston (1983) with field grown spring barley, the concentration of K in the shoot tissue water of sugar beet was fairly constant throughout the vegetative growth. The value of about 230 mmol K per kg tissue water for sugar beet was also similar to that found for beets growing over a range of sites with different soil types and under a wide range of growing conditions and N supply (Kirkby et al. 1987; Milford et al. 2008). The physiological basis for the interaction between N and K only becomes clear when K is expressed on a water tissue basis. Expressed in terms of dry matter, K concentration declines during growth and is affected by N supply. The need for K uptake to maintain the concentration of K in the cytoplasm and vacuole during growth also explains the erroneously used term in the older agronomic literature "luxury consumption of K", which expressed increase in K uptake without a corresponding increase in dry matter yield.

The important role of K in phloem loading and transport needs special mention in relation to crop production. The stimulatory effect of both K and Mg on the activity of the plasma membrane bound ATPase of the sieve tube cells is of crucial importance (Marschner 1995). The proton pumping ATPase located in the plasma membrane of the sieve tube cells creates a steep transmembrane potential gradient as well as a pH gradient between the lumen of the sieve tube (symplasm and apoplasm), the gradient acting as a driving force for the transport of sucrose from the apoplasm into the sieve tubes. Potassium, Mg, amino acids and sucrose are quantitatively the main constituents of the phloem sap which are transported from the mature source leaf to sink sites (Jeschke et al. 1997). An adequate supply of K and Mg in the leaves is thus essential in supplying sucrose to the roots to cover the energy requirement for root growth and development as well as ion uptake (Cakmak et al. 1994). During the reproductive stages of crop plants, K and Mg in source leaves play a critical role not only in ensuring an adequate supply of sucrose but also in supplying K, Mg, N, S and P to the filling of grains fruits and tubers. Recent findings that micronutrient demand (Zn, B, Cu) can also be particularly high during the early reproductive growth (Kirkby and Römheld 2004) means that the transport of these nutrients into storage tissues also depends closely on the K (and Mg) status of source leaves.

Needs for future research on potassium

Lack of transfer of knowledge, between scientist and farmer, of already well established research findings concerning soil and plant K, can present a major limiting step in agricultural production as referred to above. A further limiting step, however, pointed out by Cakmak and Schjoerring (2008) is that despite the key roles of K in biochemical and physiological processes in plants which affect crop growth, there has been surprisingly little published research on the importance of K on crop production and nutritional quality. From various discussions during the recent International Potassium Symposium at Bhubaneswar, Orissa, India (IPI-OUAT-IPNI Intern Symposium, 2009), it was also obvious that there are still future needs for fundamental work including study of K in mitigating various abiotic and biotic stresses as well as the application of this work to basic field research on K in soils and crops. Potassium also plays a very important role in human and animal health particularly in relation dietary contents of Na and Mg. Below we discuss some of the current research developments on K in soils, plants, and human and animal nutrition and discuss needs and prospects for future research.

Soil aspects

K fertilization recommendations

Exchangeable K (EK) and slowly exchangeable K (SEK) Soil extraction methods, particularly for exchangeable K (EK) are widely used as the basis for K fertilization recommendations for crops. These have proved to be quite successful for many soils not containing 2:1 clay minerals where adequate calibration has been carried out (Mengel and Kirkby 2001). However, when the contribution of SEK in soils is raised by the presence of 2:1 layer silicates that have the ability to retain K, the "power of prediction" using EK soil extraction methods is lost.

On some such soils the SEK pool (i.e. K in interlayer sites) can make a considerable contribution (80-100%) to available K to plants (Hinsinger 2002). As discussed above, this pool plays a particularly important role under K-mining conditions when the EK is low. The significance of the contribution of SEK has been underestimated perhaps for two main reasons. In the first place unlike EK there is no easy routine laboratory method for its determination and secondly the means by which K release takes place from interlayer sites is not well understood and in need of further research. Reports in the older literature indicate that cereals and grasses are more effective than dicotyledonous plants in exploiting interlayer sites for K (see Mengel and Kirkby 2001) which might relate to the higher root length density of the grasses. Rengel and Damon (2008) in their recent review deal with this different contribution of SEK of crop plants as a long-term process dependent on genotype. There are observations that in general for example sugar beet is more efficient than wheat and potatoes in the use of SEK (Steingrobe and Claassen 2000). Trehan and Sharma (2002) and Trehan et al. (2005) suggest that in contrast to K inefficient potato cultivars, efficient ones appear to bring about chemical mobilization of SEK most probably via secreted root exudates. On the other hand Springob and Richter (1998) found that a drop of K concentration below 4 µM in the rhizosphere solution triggers the release of K from SEK.

Current research by Barré et al. (2007) investigating interlayer K in 2:1 clay minerals uses X-ray diffraction techniques over short term periods to study the effect of plant roots on K depletion, aims to attempt to relate clay mineral modifications to plant uptake of interlayer K. Quantification of interlayer K dynamics is of importance in understanding the soil K cycle and critical for modeling K acquisition by crops on soils containing 2:1 clay minerals. From a practical viewpoint, further work in this area might be useful in allowing a prediction of long-term K release capacity in field balance calculations (Öborn et al. 2005). Furthermore as also discussed by these authors the potential for particular crops to extract K from the SEK fraction should also be explored for possible introduction as a green manure in the crop rotation.

Plant root – soil interactions and K availability An important reason to question EK and indeed also SEK as defined measures of K availability in soil is the underlying assumption that is often made that the supply of K to plant roots is solely dependent on K availability which can be assessed by chemical extraction of air dried soil without taking into account the interaction of the living plant root. There is a general misconception amongst some soil scientists that the prediction of suitable K fertilization rates is simply a matter of refining soil testing using chemical extraction procedures. This approach, however, takes no account of the importance of limitation of spatial availability of K as a consequence of variable root characteristics. Root morphology differs enormously between crop species especially between monocots and dicots and between genotypes which may differ as for example in root length and density and frequency of root hairs. Root hairs play a significant role in the acquisition of K which is mainly transported from the bulk soil to the root surface by diffusion in accordance with the low K concentration in soil solution (usually less than 1mM). The presence of root hairs considerably increases the surface area of the root cylinder which in turn steepens the K concentration gradient between the bulk soil and root surface which drives K influx. In many plants, root hairs may contribute up to 70% of the total surface thus increasing the root cylinder surface area 27 fold (Jungk 2001). Root hair formation has energetic implications in relation to plant growth in that of all the possible ways of increasing root surface area, it is least metabolically demanding (Lynch and Ho 2005). The root length can also vary considerably, that of winter wheat for example being 6 times greater than that of the roots of the potato crop which are relatively poor in root hairs (Johnston et al. 1998). Likewise vegetable crops with shorter growth periods have smaller root systems. The high importance of root length density in determining spatial availability of K for maize growing in a sandy soil has been demonstrated by modeling work with data from a field experiment. A root length density greater than 2 cm cm^{-3} allowed delivery of K from 50% of the topsoil volume which was reduced to only 10% when the root length density fell below 1 cm cm^{-3} (Fusseder and Kraus 1986).

Acquisition of K from soil is also dependent on numerous physical and chemical soil factors which to a large extent determine the development and spatial distribution of roots in the soil and thus their ability to acquire mineral nutrients. Soil factors inhibiting root growth such as acute B deficiency, Al toxicity in acid soils, soil compaction, salinity and drought all depress K acquisition from the soil because of their effect in lowering spatial availability of K (Römheld and Neumann 2006). For example, Batey and McKenzie (2006) reported poor growth and low K content in reseeded grass as a consequence of drought stress caused by surface compaction by over-cultivation of a moist fine sandy loam. Although the soil was adequately supplied with nutrients, the grass K content from the compacted soil was only 1.3% as compared with 4% of grass grown on a seedbed from the same soil which had not been compacted. Our own observations of visual K deficiency symptoms occurring in legumes and other dicotyledonous crops under drought spells even on K rich soils further emphasises the importance of considering root growth and weather data in future applied research to improve evaluation of plant K availability. Under such conditions of transient drought-induced K deficiency, investigation of foliar application of K might well be worthwhile. This lack of understanding in neglecting spatial K availability was apparent in discussion at the recent International Potassium Symposium at Bhubaneswa, Orissa (IPI-OUAT-IPNI Intern Symposium, 2009), in relation to the effects of low pH and possible Al toxicity in depressing root growth in the soils of Orissa as the cause of induced K deficiency.

The importance of root growth in relation to K availability is stressed from the results of the mechanistic modeling experiment of Barber and Mackay (1985) which separated the influences of soil moisture on K uptake by corn (*Zea mays* L.) between effects on root growth and the rate of K diffusion in the soil. Lowering the volumetric soil moisture level from 0.27 to 0.22 (i.e. from -33 to -7.5 kPa drought conditions), induced low K acquisition which was due mainly to decrease in root length density as a consequence of inhibited root growth in the dry soil (46-69%) and to a lesser extent to the lower effective diffusion coefficient of K (11-27%).

An innovative approach for recommendation of K fertilizer to soils of direct use to farmers has been tested and partially applied in Germany as the KALIPROG® system (Andres 1988). Use of data from a soil extraction method involving the release of SEK in this information system is linked with site-specific factors such as amount and quality of K-bearing minerals as well as weather factors affecting root growth. Extensive field trials over many years for site-specific optimal K fertilization allow the required recommendation (Andres and Orlovius 1989). For general application of this KALIPROG® system further GIS data including data on mineralogy and long term weather forecasting for particular agricultural areas is needed as well as calibration with field experiments. This appears to be a topic for urgent research which if correctly applied could be of direct benefit to farmers. The establishment of this system for K recommendation from these various parameters should bring to an end the futile debate on the benefits of improved soil extraction methods in relation to K fertilizer use.

Modelling K acquisition during plant growth The pioneering work of Barber in the USA and Nye in the UK , has been described in the publications of Tinker and Nye (2000); Barber (1995) and Jungk and Claassen (1997), in which various mechanistic mathematical models have been described to predict nutrient acquisition (usually P and K) by plants from the soil. These models take into account physiochemical processes in the soil as they influence the transport of nutrients through the soil to the rhizosphere plasma membrane interface and uptake across the plasma membrane. By and large, the models have been successful in their prediction of nutrient uptake under conditions of adequate nutrient supply but have under-predicted in nutrient restricted conditions mainly because of morphological and physiological plant adaptations which increase nutrient acquisition not taken into account by the model. These adaptations include increase in effective root surface area as in the development of root hairs, upregulation of nutrient transporters in the plasma membrane and the release of root exudates into the rhizosphere to increase nutrient concentration in soil solution by their reaction with the soil. Although adaptive root responses are of lesser importance for K as compared with N and P deficiency, when K supply is restricted , root hair proliferation is increased and K transport across the plasma membrane is upregulated (see White and Karley 2010).

An example of a model to predict K uptake during growth is that of Claassen (1994) which takes into account nutrient uptake by both roots and root hairs, and has been used recently in pot experiments to study K uptake efficiency and dynamics in the rhizosphere of maize, wheat and sugar beet (Samal et al. 2010). The model is based on three basic processes: (i) release of K from the solid phase into the solution phase, which is governed by sorption and desorption processes, (ii) transport of K by mass flow and diffusion, mainly diffusion, and (iii) K uptake into the root which depends on the nutrient concentration in the soil solution and is measured by a modified Michaelis-Menten equation. The radial distribution of root hairs around the root is also accounted for and an influx established. In the experiment plants were grown on a low K soil with and without K. Soil parameters used in the model calculation included: mean root radius, water influx, relative shoot growth rate, relative root growth rate, root hair distribution around the root, plant parameters related to uptake kinetics and net K influx.

The model demonstrated major differences in K uptake efficiency for the three crop species. Sugar beet and wheat maintained a higher shoot K concentration as compared with maize and therefore had a higher K uptake efficiency. Wheat acquired more K from the soil because of its higher root length to shoot dry weight ratio whereas sugar beet accumulated more K in the shoot because of a 3- to 4-fold higher K influx in comparison with wheat and maize. At the higher K supply, the model closely predicted K influx but under-predicted it at low K supply and particularly so for sugar beet most probably because of an increase in K concentration in the rhizosphere induced by chemical mobilization of K by root exudates. Likewise, a simulated mechanistic model of K uptake at low K supply by field grown sugar beet throughout the growing season accounted for only 34 % of the K uptake (Dessougi et al. 2002). These finding confirm the earlier work of Steingrobe and Claassen (2000) and further research is needed to elucidate the underlying mechanisms between sugar beet roots and soil at low K supply by which K release takes place into the soil solution.

One easy-to-calibrate mechanistic model for calculating arable crop response to K fertilizer in the field was described by Greenwood and Karpinets (1997a). The model calculates for each day the increase in crop K-uptake and growth and changes in K activity ratio of the soil solution, exchangeable soil K and fixed soil K. The validity of the model was tested against the results of single year multi level K field experiments (Greenwood and Karpinets 1997b). Measurements of plant mass, % K of the plant and K activity ratio in the soil were made at intervals during the growing season and at harvest on spring wheat, summer cabbage and turnips. The degree of agreement between simulation and measurement was substantial. Some discrepancies did occur, however, interestingly enough in context of the above discussion, on root growth, probably because of uneven root distribution. One of the assumptions in the model was that the roots were evenly distributed

throughout the rooting layer and that K was not taken up from the subsoil. Nevertheless the model provides an excellent approach and is of direct value to the farmer. Simulations of the model indicate that in central England, no response of 10 crops to K fertilizer would be likely on soils containing more than 170 mg of 1M ammonium nitrate extractable K /kg soil and having clay contents between 15 and 45% (without any major contribution of K from interlayer sites). A simplified version of the model runs on the Internet at: www.qpais.co.uk/moda-djg/potash.htm.

Plant aspects

Plant breeding for K efficiency

Plant breeding of crops has for generations been carried out in non limiting environments which has led to the selection of highly productive genotypes that are also highly demanding of plant nutrients including K. Interest is now focusing on improving efficiency of fertilizer application and timing for nutrient uptake as well as the introduction of nutrient efficient cultivars capable of yielding on poorer soils with low fertilizer regimes as often occurs in the developing countries (Lynch 2007). Genotypic differences in efficiency of K uptake and utilization have been reported for all major economically important crop plants and the underlying physiological mechanisms for these differences have been reviewed in detail by Rengel and Damon (2008). These authors define K efficiency as the capacity of a genotype to grow and yield well in soils of low K availability. Both efficiency in K uptake and utilization of K within the plant are involved.

Efficiency in uptake particularly of the less mobile nutrients like K and P is much dependent on root architecture i.e. the configuration of the root system in time and space (Lynch 1995). Root traits determining genetic differences in P acquisition by bean (*Phaseolus vulgaris* L.) have been identified in detail (Bates and Lynch 2001) and the findings of Lynch and his colleagues have been successfully applied to breeding P efficient genotypes used in the field as for example, P efficient soybean lines which have yielded 15-50% more than existing genotypes in P deficient soils in south China (Yan et al. 2006). Comparative studies for K should be worthwhile because the acquisition of both nutrients requires a large surface contact area between roots and topsoil and exploration of the subsoil where water may be more available. Root hair formation differs between crop genotypes for K (Jungk 2001) but there appears to be no literature assessing the formation of root hairs as a mechanism for intraspecific differences in K uptake (Rengel and Damon 2008).

Uptake of K across the plasma membrane is a highly efficient process and not considered as a limiting step in acquisition under adequate K supply. Under K deficient conditions however, plant species and genotypes differ in capacity in the high affinity uptake mechanism. In potato grown under K deficiency, a K efficient genotype had about a two-fold higher K uptake rate than a K inefficient one (Trehan and Sharma 2002). Under K deficiency genotypes may enhance K uptake either by morphological or physiological response. In comparing two strains of tomato (Chen and Gabelman 1995) showed that one strain responded morphologically by proliferating root length thereby producing greater root absorbing surface areas to capture K. The other, a physiological response was demonstrated by high net K-influx coupled with low pH around root surfaces, presumably a K^+/H^+ exchange with high accumulation of K in the apoplast.

Genotypic differences in capacity to utilize K have been attributed to (1) differences in partitioning and redistribution of K at cellular and whole plant levels, (2) the substitution of K by other ions e g Na in the vacuole particularly important under salinity (3) the partitioning of resources into the economic product (Rengel and Damon 2008). Differences in K distribution between genotypes can influence capacity to produce high economic yield per unit K uptake. For example, Yang et al. (2004) reported that K- efficient rice genotypes grown under conditions of low supply of K, had a two fold higher concentration of K in the lower leaves and a 30% higher concentration in the upper leaves as compared with inefficient –K rice cultivars at the booting stage. These higher K concentrations in the leaves (especially the lower leaves) of the K-efficient genotypes were associated with higher RuBP carboxylase activities and net photosynthetic rates allowing the leaves to maintain a higher photosynthetic capacity during grain filling. Damon and Rengel (2007) showed that in terms of grain yield of field and glasshouse grown wheat genotypes, the main factors determining tolerance to K deficiency were a high harvest index at K deficiency and the high ratio of harvest index at deficient to adequate K supply.

In general from an agronomic viewpoint, high K crop use efficiency is beneficial particularly on soils low in K availability. In contrast, to this however, as discussed by Cakmak (2005), crops of high K nutritional status are required to provide resistance to the various common stress events which are considered below. The same is valid in relation to the high K/Na ratio required in food products in the human diet. It has also to be remembered in plant breeding programmes aimed at raising K use efficiency, that unlike lack of efficiency in N and P use by crops which can be detrimental to the environment, this is not so for K which is completely benign, posing no threat to human health or the quality of natural waters.

Role of potassium in stress mitigation

Crops exposed to various environmental stress factors such as drought, heat, high light, chilling or salt all show increased formation of reactive oxygen species (ROS), Cakmak (2005). This formation of ROS takes place particularly during

photosynthetic electron transport as well as by activation of membrane-bound NAD(P)H oxidases (Jones et al. 2000). There is increasing evidence from the literature that optimizing the K nutritional status of plants can reduce this detrimental build up of ROS either by enhancing photosynthetic electron transport or inhibiting the membrane-bound NAD(P)H oxidases.

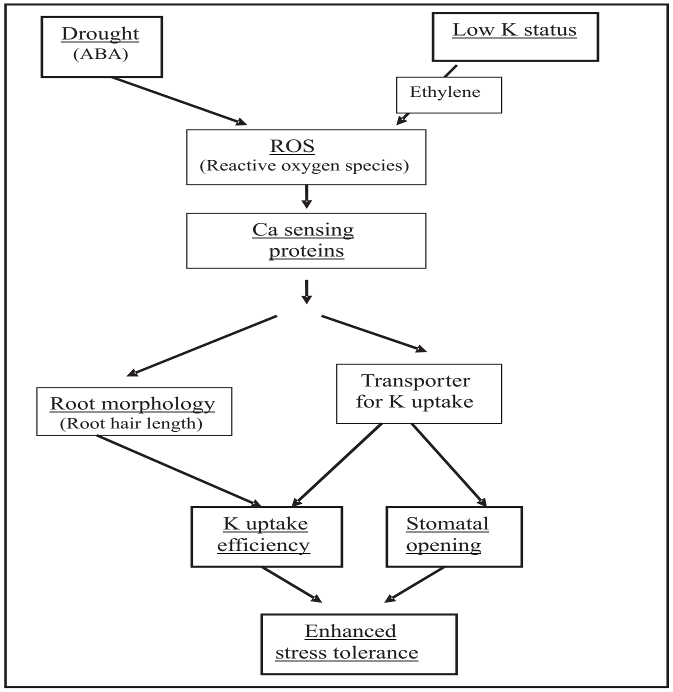
It is well documented that K deficient plants are more susceptible to high light intensity with associated occurrence of photooxidative damage such as chlorosis and necrosis (Marschner and Cakmak 1989). One reason for this enhanced ROS formation under high light is the inhibition of photosynthesis and photoassimilate export from the leaf under K deficiency. Inhibition of sugar export via phloem prevents root morphological adaptation of crop plants to K deficient stress conditions, in marked contrast to N and P stresses where sugar translocation to the roots is not restricted. Inhibited sugar export under K deficiency also restricts shoot growth and the formation of reproductive organs such as grains.

There is ample evidence that ROS production is raised in plants low in K exposed to various environmental stresses as for example to low temperature, drought and salinity (Cakmak and Engels 1999; Cakmak 2005), From these above examples it can be concluded that optimizing plant K nutritional status is needed to raise stress tolerance of crop plants as discussed in more detail below. This conclusion is further underlined by the involvement of K in stress signaling

Role of potassium in stress signalling

Evidence is emerging from studies in molecular biology that K might play a specific regulatory role in plant stress responses (Ashley et al. 2006; Wang and Wu 2010). These authors review links between low K plant status and activation of signalling cascades. Low K status not only triggers an up-regulation of K transporters, but also involves the synthesis of molecules including reactive oxygen species (ROS) and the phytohormones jasmonic acid (JA), ethylene and auxin. In addition to these up-regulation of transport proteins and adjustment of metabolic processes, K deprivation triggers developmental responses in roots, all these strategies enabling plants to survive and compete in nutrient environments in which the availability of K may vary. Evidence of changes in expressions of transcripts encoding K^+ transporters and channels in response to ROS and phytohormones are also suggestive that K may play a specific regulatory role in plant stress responses which is very much in accord with field observations as discussed in the sections below. The hypothetical model shown in Fig. 2 is derived from the recent findings of Cheong et al. (2007) and Jung et al. (2009) of molecular changes in response to K deficiency in Arabidopsis thaliana. The work of Cheong and his colleagues indicates that in K deprived plants, drought - induced ABA may produce ROS which in consequence may trigger Ca flows as second messenger and subsequently the uptake of K by roots and the regulation of stomatal guard cells. This Ca signalling which regulates leaf transpiration and root K uptake involves membrane localized Ca sensor interacting proteins. Jung and co-workers reported ethylene production in K deprived plants. This phytohormone signals stimulated production of (ROS) and is important for changes in root morphology and whole plant tolerance to low K supply. Our scientific understanding of the role of K in stress mitigation will – without doubt – improve in the near future which will be of major importance for agriculture. In the following subsections below these needs for research are discussed in relation to well-known specific stress situations.

Fig. 2 Schematic model for a proposed common signalling pathway induced by drought and low K nutritional status of plants regulating K uptake and drought stress tolerance. (from findings of Jung et al. 2009 and Cheong et al. 2007)



Role of K in disease and pest resistance

It is widely accepted that in general, high K status in crops decreases the incidence of diseases and pests (Perrenoud 1990;Prabhu et al. 2007;Bergmann 1992). This benefit of K has been explained by its effect on primary metabolism by favouring the synthesis of high molecular weight compounds (proteins, starch and cellulose) thereby depressing the concentrations of soluble sugars, organic acids, amino acids and amides in plant tissues. These low molecular weight compounds necessary for feeding pathogens and insects are thus more prevalent in K deficient plants which are thus more vulnerable to disease and pest attack (Marschner 1995). For example on K deficient soils, cotton and other crops can be susceptible to Fusarium wilt and root rot, caused by *Fusarium oxysporum sp.;* application of K either before or after planting has been shown to be equally effective in reducing this incidence (Prabhu et al. 2007). As pointed out by Amtmann et al. (2008), however, because of the variability of both disease susceptibility and metabolic profiles in K deficient plants, it is impossible at this stage to prove their causal relationship and there is a great need for such basic and applied studies to be undertaken in agricultural crops.

This often observed variability in the effect of K on incidence of diseases and pests certainly relates to the differences in K nutritional status of plants or to the amounts and the forms of applied K or to both these factors (Amtmann et al. 2008, Perrenoud 1990). In most cases of compiled observations of experimental trials with increasing supply of K, the K nutritional status of plants has either not been analysed or not given (Huber and Arny 1985; Kiraly 1976, Prabhu et al. 2007). Some recent studies on the incidence of black spot in potatoes as affected by the K nutritional status by K+S Kali GmbH, Kassel, Germany as reported by Ebert on the IPI-OUAT-IPNI symposium at Orissa (2009), are exceptions to this. The frequent lack of data on the K nutritional status of plants in many investigations, however, means that it is often not possible to relate the effects of K treatment adequately to disease incidence. In practice this is required for a cost-benefit calculation for the farmer (Amtmann et al. 2008) which also needs to take into account other aspects of stress mitigation by K supply as discussed below. There is thus a real need for more detailed and comprehensive data from applied research and field experiments relating K supply to plant disease.

The plasma membrane is not only a barrier to ions and water transport but is also a recognition site for potential pathogenic invaders of plant cells. As a consequence of such possible attack, changes in the membrane potential with concurrent rise in cytoplasmic Ca occur within seconds, which in turn acts as a second messenger triggering a number of downstream events (Yang et al. 1997). Calcium transporting proteins can respond to other early defence signals such as H_2O_2 (Foreman et al. 2003, Scheel 1998) and K is likely to be involved in all these signals. The observations of Shin and Schachtman (2004) indicate that K deficiency results in early defence signalling including phytohormones such as ethylene in Arabidopsis roots. In addition, genes related to jasmonic acid are also induced at low K status (Lorenzo et al. 2003; Armengaud et al. 2004; Schachtman and Shin 2006).

Following the observations of Amtmann et al. (2008) and others that K deficiency results in early defence signaling, there is need to consider how these nutrition- and pathogen-induced responses within general signaling networks may be applicable to agricultural practice. Basic research is necessary to confirm that the K deficiency-induced changes in transcripts, metabolites and hormones in the defence mechanisms of the model plant *Arabidopsis thaliana* is similar to those in crop plants. Amtmann et al. (2008) conclude that even without genetic engineering, available data could be useful for improving timing of K fertilizer applications. They suggest a limited but essential supply of K early in the growth season followed by K depletion at a later growth stage could be a means to strengthen the inherent defence potential of the plants to pathogens. This suggested fertilization strategy is far from that of current thinking of farmers and their consultants. This very interesting and new aspect on K-disease interactions emphasises the urgent need for further collaborative research between molecular biologists, plant nutritionists and agronomists.

Role of K in frost resistance

Both chilling and frost stress events result in photooxidative damage to chloroplasts as a consequence of high light energy absorbance in excess of the capacity of chloroplasts to use it for CO_2 fixation at low temperature. This excess energy is used for ROS formation (Huner et al. 1998, Foyer et al. 2002) which impairs the photosynthetic electron transport chain, stomatal conductance and rubisco activity (Allen and Ort 2001).

The role of K in protecting crops against frost damage has been recognised for many years and discussed in plant nutrition textbooks (Bergmann 1992, Marschner 1995). This alleviating effect of K is shown in Table 7 from results of a field experiment on potato growing on light sandy soils varying in K status in Punjab, India (Grewal and Singh 1980). Potassium fertilization increased frost resistance on all three soils and particularly so on the soil of lowest K status. The marked effect of increasing K fertilizer application in mitigating frost damage on the soil of medium K status but without effect on tuber yield is indicative of the requirement of the higher K supply to raise frost resistance at low temperature In this experiment which included 14 alluvial soils varying in available K, frost damage was inversely related to the available K content of the soils and the K concentration in the potato leaves and damage was significantly reduced by K fertilization. Similar effects have been reported by Sharma and Sud (2001). In various non glasshouse grown vegetable crops (tomato, pepper, egg plants) at temperature ranging from 4°C to 16°C, (Hakerlerler et al. 1997) have observed that increasing K fertilizer use raised low-temperature-stress tolerance which resulted in as much as 2fold increases in yield.

Table 7 Effect of increasing K supply on frost damage (%) and K content of leaves (mg g^{-1} DW) and tuber yield (t ha^{-1}) of potato on sites with different soil K status (Grewal and Singh 1980).

K status of the site		K fertilization rate (kg ha^{-1})		
		0	42	84
low	Frost damage *	65	26	12
	K content	1.64	1.96	2.85
	Tuber yield	18.0	22.9	29.6
medium	Frost damage	52	30	4
	K content	2.28	2.80	2.80
	Tuber yield	19.8	26.0	26.3
high	Frost damage	12	12	0
	K content	2.61	2.79	2.82
	Tuber yield	20.7	22.4	23.4

* Percentage of foliage damaged by frost in the field

In agreement with these findings, the benefit of higher K tissue concentrations on yield and chilling damage on white carnation has been reported by Yerminyahu and Kafkafi 1990 (cited by Kant and Kafkafi 2002). Their results showed that plants with what might be regarded as high K tissue concentrations under non-stress situations can be economically of advantage to the farmers by acting as an insurance strategy against unexpected climatic events. At lower but normally acceptable K tissue concentrations, only one night of chilling temperature can cause severe enough damage to the crop to be equivalent to the fertilizer cost for the entire season. Interestingly the effects of this damage on the stem of the carnation is not obvious until several weeks after the low temperature stress event.

Nowadays in farming practice frost resistance can be a critical factor in the early (late spring frosts) as well as the late season (early autumn frosts) particularly in regions with short vegetation periods. Many farmers are thus at the mercy of increasing frost damage. Various observations have been made which indicate alleviating effects or even the prevention of frost damage by the application of various cocktails containing K together with other mineral nutrients including Ca, P and micronutrients. The beneficial effects of these cocktails have been obtained by both pre- and interestingly also, post-frost applications of foliar sprays as well as by seed dressing (Randy Saskiw, Omex company, 2009, pers. comm.).

Experiments in East Germany, Ukraine and Russia on winter rape (canola) have demonstrated the mitigating effect of Cu on frost damage when applied as a foliar spray, particularly under conditions of adequate K fertilizer supply. In wheat this beneficial effect of Cu could be further enhanced by supplements of B (Bernhard Bauer, 2009, pers. comm.). All these field observations are in accordance with reports by Bergmann (1992) and Bunje (1979) and strongly suggest that K should not be considered in isolation in relation to its effect in raising frost resistance.

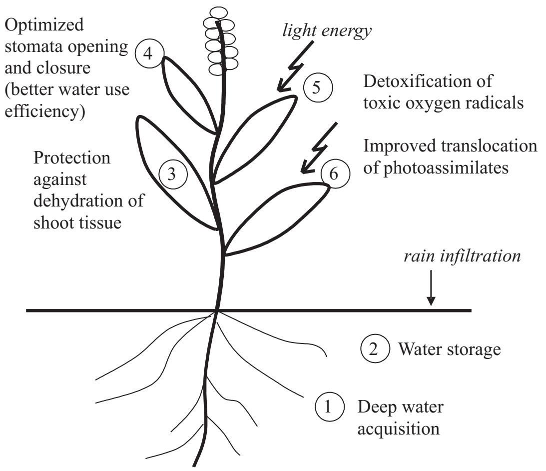
A major function of K as an osmoticum is the maintenance of a high concentration of K in the cell sap thus lowering its freezing point. Additionally the activities of numerous enzymes which might play a part in frost resistance are also dependent on adequate K cytoplasmic concentration (Kant and Kafkafi 2002). The higher ratio of unsaturated to saturated fatty acids with phospholipids rich cell membranes in plants of high K status can also partially explain raised frost resistance as a consequence of enhanced membrane fluidity. Other mineral nutrients than K also possess distinct physiological properties of direct relevance to frost resistance. Boron, Zn and in exceptional cases also Ca may raise frost resistance by stabilizing cell membranes. Additionally cold induced stomatal closure induced by apoplastic calcium uptake by guard cells (Wilkinson et al. 2001), can contribute decisively to chilling tolerance and protection of leaves from dehydration. Copper, Mn and Zn may also increase frost resistance in their role in superoxide dismutase enzymes which detoxify oxygen radicals thereby preventing damage to membranes and other cellular constituents (Cakmak 2000, Kant and Kafkafi 2002). The functions of these mineral nutrients in plant metabolism justifies their use in nutrient cocktails in mitigating frost resistance both on scientific grounds and in accord with field observations as discussed above. However, much is still to be learned as for example the interrelationships between the micronutrients and K to enable adequate recommendations to farmers. Basic as well as applied research is urgently needed in this area.

Role of K in drought and heat stress

Worldwide, crops are increasingly being exposed to drought and high temperature stresses with enhanced formation of ROS and corresponding leaf damage (Foyer et al. 2002; Cakmak 2005). The hypothetical model in Fig. 2 tentatively indicates the interplay of drought-induced ABA and low K nutritional status of plants in stress signaling. Drought and heat stresses are often considered together as a drought-heat syndrome because they often occur simultaneously, but this is not always so. As discussed by Halford (2009), plants also have to cope with hot conditions where water is not limiting which is of particular relevance to crops growing under irrigation. In many parts of the world, especially in temperate conditions, however, drought and heat stresses act together to restrict agricultural production. In the “high maize yield” model by Yang et al. (2006) therefore both aspects – drought and heat – are treated separately so that farmers can make appropriate allowance for these two stress factors.

During crop production various plant physiological and soil aspects have to be considered in mitigating or preventing damage by drought or heat stresses or both as illustrated in Fig. 3. The numbers in circles on this figure refer to processes discussed in the subsections below in all of which K is directly or indirectly involved. In general, maintaining adequate K plant nutritional status is vital in adaptation to drought (Sen Gupta et al. 1989; Kant and Kafkafi 2002; Cakmak 2005). When drought impedes K acquisition by restricting root growth a vicious circle comes into play in which the resulting lower plant K nutritional status further depresses physiological resistance to drought and the acquisition of K. The particular requirement for additional K fertilization under drought conditions is often not appreciated by farmers (see also "introduction").

Fig. 3 Possible factors for an improved drought and/or heat resistance of plants (numbers in circles refer to subsections of section "Role of K in drought and heat stress".



Forced deep rooting In suitable soils a worthwhile approach drought resistance of crop plants is to induce deeper rooting to allow access to available water at lower depths in the soil profile. This can be achieved by deep placement of K fertilizer together with small supplements of mineral nutrients with root-signalling functions such as P or N or both these nutrients to encourage root growth, because K itself does not have a root-signalling function (Drew 1975, Kirkby et al. 2009). Ensuring adequate supply of K during drought events is essential in supporting the role of K in translocation of photoassimilates to feed root growth. This need for K is evident from the findings of Egilla et al. (2001) in experiments with Chinese Hibiscus, (*Hibiscus rosa-sinensis cv* Leprechaun), growing under various K regimes. Root survival was markedly reduced when water supply was limited and K supply low, an adequate K supply being essential to enhance drought resistance and increase root longevity. The benefits of deep K fertilizer placement have already been demonstrated in some field experiments in which K fertilizer placement was achieved at a depth between 25 and 45 cm. The technique and the economical evaluation of deep rooting still need further invest-igation under varied conditions including high and low input agricultural systems.

Improved rainwater capture To increase plant K acquisition particularly from depth from the soil profile requires high rainfall infiltration as well as high water storage capacity within the profile, the latter being dependent on soil texture and structure and to some extent also on soil organic matter (Hermann et al. 1994). In this respect the recycling of K-rich crop residues serves a double function in supplying K and supporting the organic matter status of the soil.

Protection against tissue dehydration It is well documented that under low K nutritional status, particularly during the midday, leaf damage can take place due to wilting with subsequent tissue dehydration and necrosis. The general physiological function of K in plants in maintaining water relations (osmotic regulation) has been discussed in "potassium in plants: present knowledge" and is particularly important for optimal photosynthetic activity as shown by the findings of Sen Gupta (1989) (Table 6). Under drought stress events it is essential that leaf K status is adequate to counter the "vicious cycle" mentioned above.

Regulation of stomatal opening and closing Adequate K nutritional status of crop plants is closely associated with plant water use efficiency (Thiel and Wolf 1997). Much work has been carried out on the physiology of K in relation to stomatal movement. The transport of water and potassium from roots to shoots mediates in CO_2-water exchange governed by transpiration through the stomatal pores. In natrophilic crop plants like sugar beet, Na as well as K has to be considered in adaptation of stomatal closure and opening under drought (Hampe and Marschner 1982). It seems to the authors that no further basic research is needed in this area.

Detoxification of oxygen radicals Under high light intensity increased formation of toxic oxygen radicals can bring about damage to leaves as chlorosis particularly if photosynthate transport is limited as a consequence of K, Mg or Zn deficiency (Cakmak 2005). Such damage by high sunlight has been reported as sunscald in fig fruits of low K status in Turkey by Irget et al. (2008) clearly showing the need for adequate K nutrition under high light intensity. In addition to K, however, various micronutrients including Zn, B, Cu and Mn are also of vital importance in the detoxification of oxygen radicals (Marschner and Cakmak 1989; Cakmak 2005). This is another example showing the need to consider K not in isolation but together with other mineral nutrients in mitigating heat/light stress as well as drought stress in future applied research.

Enhanced translocation of photoassimilates During the reproductive stage of crop growth the high demand for photoassimilates by developing seeds and fruits is often accompanied by severe chlorosis in the leaves (Table1). These chlorotic symptoms are the consequence of inhibited translocation of photoassimilates from leaves via the phloem to the seeds or fruits and are observed particularly at low nutritional status in K, Mg or Zn (Marschner and Cakmak 1989, see also above section 5.1). As proposed by Cakmak (2005) farmers should ensure that leaf concentrations of both K and Mg are adequate and if necessary make foliar applications of K and Mg separately to mitigate against such chlorotic symptoms during reproductive growth. In wheat such late foliar application of Mg has been shown to prevent Mg chlorosis under drought events (Römheld and Kirkby 2007). As discussed during the IPI Intern. Symposium (2006) a late K foliar application in banana and sugar cane increased the yield or at least the sugar content in harvested products (Yadav 2006; Kumar 2008). Without doubt further field studies with different crops are needed in this area of applied research.

Role of potassium in salt stress resistance

Detrimental effects of salt stress on growth of crop plants are an increasing problem for agriculture, particularly in irrigated land (Kant and Kafkafi 2002, Shabala and Cuin 2008). There are two components to this detrimental effect, a short term osmotic effect with consequence of decreasing water availability to plants and a long term ionic effect, which results in salt toxicity (mainly Na and Cl) and deficiencies of other mineral nutrients particularly K and Ca (Kafkafi and Bernstein 1996). Roots, directly exposed to a saline environment, react by restricting growth as a consequence of a water deficit i.e. lower water availability caused by the more negative water potential in the rooting medium. This in turn results in lower nutrient uptake and inhibited translocation of mineral nutrients to the shoot in general and of K in particular. A lowering of photosynthetic activity is a consequence. Thus under salinity, closure of stomata and inhibited photosynthetic activity due to lower K nutritional status which induces the formation of toxic oxygen radicals (Cakmak 2005). A higher K supply is thus needed to counteract this effect under saline conditions (Abogadallah et al. 2010). As pointed out by Shabala and Cuin (2008) measures for mitigation of salinity should not focus only on lowering Na accumulation in photosynthetic active shoot tissue but rather on K homeostasis maintaining a high K/Na ratio (Rubio et al. 2010) by preventing K losses by Na and/or Na-induced Ca deficiency.

Programmed cell death (PCD) has been proved to occur in response to biotic and particularly to various abiotic stresses such as salinity (Shabala 2009). This response seems to be ion specific (induced by Na^+) and not due to the osmotic component of elevated salt concentration (Huh et al. 2002). As a consequence of membrane depolarization, massive K efflux by the outward-rectifying K^+ channels KORCs can be observed. In this PCD induced by salinity (NaCl), Zn can play an additional role by increasing the cytosolic K^+/Na^+ ratio (Shabala 2009). It is also suggested that ROS and some plant hormones (e.g. ethylene, jasmonic acid) are involved in regulating salt-induced PCD. However, further direct experiments particularly with crop plants rather than Arabidopsis are needed to reveal the full complexity and cross-talks between multiple pathways controlling salt-induced PCD in plant cells (Shabala 2009). Of special interest is that as a consequence of salt-induced PCD, primary roots might be eliminated and new better salt-adapted secondary roots formed for an adequate nutrient and water acquisition (Huh et al. 2002).

Common measures in practical agriculture to reduce salinity problems for crops include Ca supplementation as gypsum and supplying adequate rates of K fertilizer application rate, both of which act to reduce salinity problems by maintaining K homeostasis. The ameliorating effect of Ca is dependent on its role in improving soil structure via clay flocculation as well as in preventing NaCl induced loss of K from plant roots as K^+ efflux via KORCs (Shabala et al. 2006). Kaya et al. (2001) have shown in tomato that foliar application of K salts is also able to counteract salinity-induced detrimental effects on plant growth, water use and membrane permeability. Besides raising K and Ca supply there are also reports of positive effects of boron and specific biofertilizers (Nabti et al. 2007) on mitigation of salt problems, particularly via seed priming. The positive effect of Si supplementation to barley plants grown in nutrient solution under salt stress has been shown to result from increasing plant K nutritional status and antioxidant enzyme activities (Liang 1999; Liang et al. 2003). In view of the function of various mineral nutrients in relation to salt tolerance by stabilizing plant membranes (Ca, B) and by depressing the formation of stress induced oxygen radicals or their detoxification (K, Zn, Cu, Mn, P), an integrated approach is needed to consider all these nutrients both in basic and applied research.

Role of potassium in crop quality

The physiological basis for the need of adequate K status of plants in quality development of crops is well recognised. To a large extent it relates to the specific effects of K which include: increasing photosynthesis as consequence of a more efficient photosynthetic activity, increasing leaf size and number and more effective translocation of photoassimilates and amino N compounds into reproductive organs via the phloem (Cakmak 2005; Pettigrew 2008). An immense number of publications report this positive role of adequate K supply in raising the quality of various crop plants (e.g. Kumar et al. 2006; Pettigrew 2008). Yadov (2006) very appropriately has described K as the “quality element”. From these numerous reports on the role of K on crop quality it seems reasonable to conclude that, rather than carrying out more applied research in this area, there is a much greater need to make the farming community more aware of the importance of the benefits of maintaining an adequate K status in crop plants .The widespread lack of

informed recommendation to farmers regarding K fertilizer use as referred to in the examples of kiwi orchards in Italy and tomato production in Chinese greenhouses underlines this conclusion.

In order to enhance crop quality, there is a need for both a greater as well as a more efficient use of K (Pettigrew 2008). Increasing uptake efficiency can raise both yields and quality, particularly under drought. However, in using K more efficiently there is a need to avoid long-term K mining by balancing K removal from the soil by appropriate K replacement. As discussed by Cassman (1998), crop genotypes with longer or improved root systems could be used to achieve more efficient removal of native soil K or applied K fertilizer. Raising efficiency of K utilization by developing specific crop genotypes with lower K demands, has the possible consequence of an undesired decline of the K/Na ratio in crops and hence also in the human diet.

Human and animal nutritional aspects

As well as being of fundamental importance for plants and crops, K is an essential element for animals and human beings, responsible among other things for an adequate electrolytic and energy status of cells and in particular of muscle cells. The K status of the animal body is well regulated via intake or resorption from the gastrointestinal tract and excretion (Serfass and Manatt 1985; Preston and Linsner 1985). This optimal regulation means that there are no major problems associated with the K status of animals and human beings as long as the K intake from the diet is guaranteed by an adequate supply of fodder or in the case of humans, by fruit and vegetables.

The human dietary intake of K, however, is often too low at about one third of evolutionary intake (He and MacGregor 2008). It is very low for example in rural populations in developing countries in which the staple diet is dominated by low K cereal products. In the more affluent modern societies the strong decline relates to great increase in consumption of processed food and decrease in fruit and vegetables in the daily diet, a change also linked to an increase in prevalence of health problems. These problems relate not directly to the lower K intake per se but are rather associated with the dramatically increased intake of sodium (Na) mainly as NaCl causing elevated blood pressure, cardiovascular and kidney diseases, hypercalciuria and osteoporosis (He and MacGregor 2008).

The benefits of increasing intake of K in the human diet (Demigné et al 2004; He and MacGregor 2008) may be achieved by raising K concentration of food crops and/or K salt additions to processed foods. This may be regarded as an important challenge for the food industry, however, account must also be taken of K-induced Mg deficiency effects in animals and human beings. Raising dietary K status restricts Mg re-sorption from the gastrointestinal tract and thus also the metabolic function of Mg in cells. The real challenge for the food industry and for plant research is to reduce Na intake and at the same time to increase dietary intake of a well balanced supply of Mg and K. Food supplements on the market focused on human health take into account this aspect of balanced food fortification by supplying Mg and K together with Zn. For future research the following areas need to be considered:

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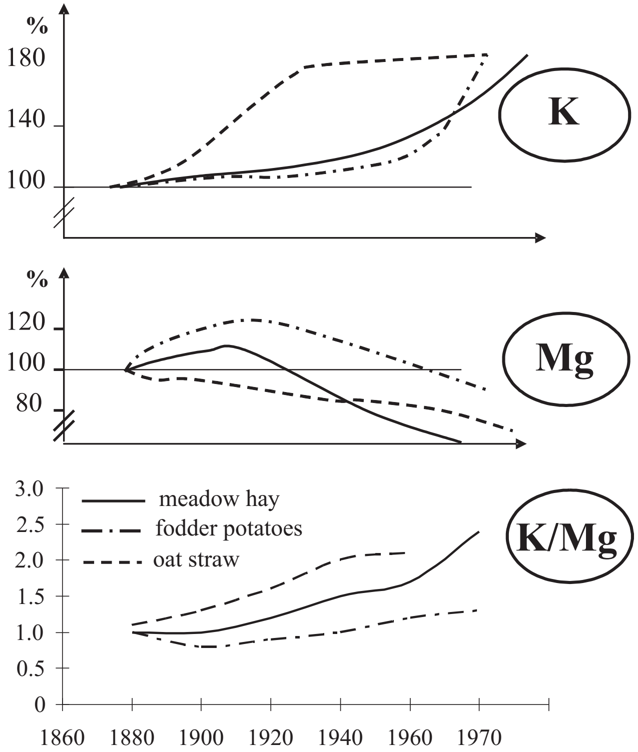
Potassium/magnesium ratio in food and fodder

As with the lack of understanding of the importance of K/Mg ratio in plant production (see example kiwi orchards, Table 1), there is similarly an undervaluation of Mg in the human diet in relation to K, although the significance of this interaction has been known for many years in animal nutrition as in relation grass tetany in lactating grazing cattle (see Gunes and Welch 1989). It is of high interest that over the years from 1880 until 1960 the Mg content in some home produced feeding stuffs of farms in South-West Germany declined by up to 40% whereas the K content increased by up to 80% leading to a change of the K/Mg ratio from 1 to about 2.4 (Fig. 4, Arzet 1972).

Fig. 4 Changes in the K and Mg concentrations and K/Mg ratio in fodder of farms in the Southwest of Germany from 1880 – 1970 (according to Arzet 1972)



A comparable change in K and Mg content in leafy vegetables may also be assumed to have taken place as a consequence of a one-sided elevated application of K fertilizers which occurred in the past. Documenting changes in concentration of K and Mg, as well as Na and Ca in the main leafy vegetables such as lettuce would be of value particularly to include periods in which K fertilizers supplemented by Mg have been applied as has occurred over the past two decades. Here field research is urgently needed.

Potassium/sodium ratio in processed foods

As discussed above there is an increasing health burden for human beings as a consequence of the dramatic increase in Na intake resulting mainly from processed food products. The first essential requirement for the food processing industry is therefore to lower Na supplementation and partly replace it by a mixture of K and Mg. Current labeling of food products giving quasi “nutrition facts” is of little value concerning mineral nutrients, for among the cationic nutrients only the Na or NaCl composition is given. In view of the major importance of K to human health, the Na/K ratio should be clearly visible on the product label. In summary there is scarcely any need for future research in crop production, the onus of supplying healthy food in this respect lies with the food processing industry!

Effect of potassium chloride on cadmium uptake by crop plants

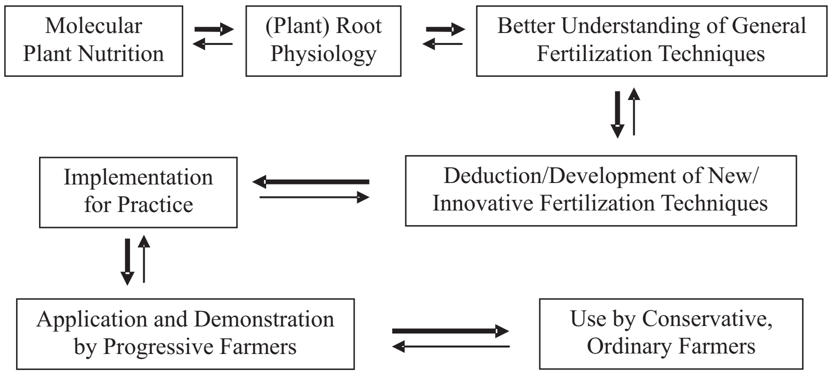
Cadmium (Cd) is an undesirable heavy metal in food products because of its high toxicity. Contradictory reports appear in the literature on the effect of K fertilizers on Cd availability in soils particularly when applied in the chloride form (Grant et al.1996; Umar et al 2008; Blank 2009). Chloride can form easily soluble chloro-Cd complexes so that plant uptake of Cd can be enhanced (Smolders and McLaughlin 1996). Chloride is also effective in increasing Cd transport within plants (Ozkutlu et al.2007). Increased Cd uptake by application of KCl was found in barley (Grant et al. 1996) and under salinity in wheat (Norvell et al. 2000). At conventional rates of application (100 – 200kg chloride ha^{-1}), Blank (2009) was unable to find any difference in effect of chloride as compared with sulphate on Cd extractability from soil. The influence of the K appears to be more important by its effect in desorption of Cd from the soil. From these findings it can be concluded that the chloride effect occurs particularly at very high application rates. At normal application rates, the effect of cations (K^+ or Na^+) are of higher relevance than the mobilization of Cd by formation of Cd-chloro-complexes. The findings of Zhao et al (2003) showing no differences in Cd uptake by spring wheat between K salts in chloride or sulphate form support this conclusion. Thus in summary, in order to give sound recommendation in agricultural practice a greater understanding is needed of the mechanisms involved in Cd / K and Na / Cl interactions.

Summary and prospects

The various aspects of plant K discussed above such as general stress signaling, enhanced disease resistance and adaptation to drought stress, clearly indicate that progress in our understanding of physiological aspects of K acquisition and its utilization, as well as the adoption of K fertilization strategies in farming practice, are closely linked to current research findings in molecular biology. Plant nutritionists, extension service scientists and progressive farmers need to be more aware of the continuous achievements being made in the understanding of basic plant physiology and its signaling network as deduced from results from this molecular approach (Fig. 2). On the other hand it is also becoming obvious that molecular biologists themselves need to have a basic understanding of the farmers' problems on a global scale so that they may become more proactive in addressing these problems and in considering the practical relevance and application of their research findings to the real world of agriculture. We are convinced that a closer interaction between those working in molecular biology and those in farming practice (Fig. 5) will help to improve the urgently needed management strategies for stress mitigation. In general, throughout agriculture there is an urgent need for laboratory specialists to have a greater appreciation of all aspects of practical crop production. As a part of this integration, a great challenge exists to be better able to deal with stress events involving K in farmers' fields.

In the use of K in crop production, there is a need to ensure balanced fertilization and efficient usage of K in relation to the supply of other nutrients especially N and Mg. The reported mitigating effects of particular micronutrients acting in conjunction with K on various stresses is of immediate importance to crop production and requires investigation. The various proposed basic and applied research aspects relating to adequate frost resistance are good examples of these needs. From the plant viewpoint, more basic research is required on the drought - heat syndrome to understand the separate influences of these two often combined stress factors.

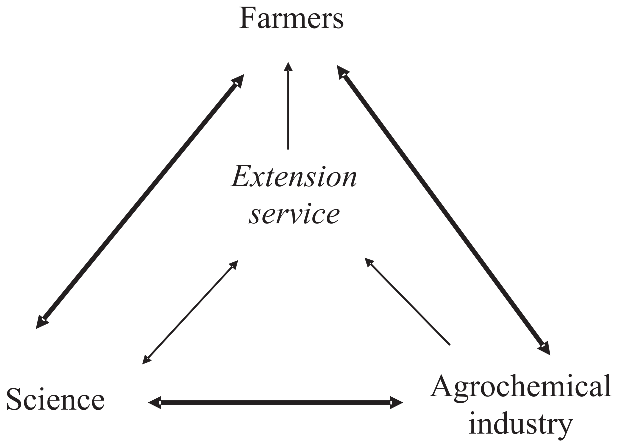
Fig. 5 Various research areas and interactions needed to improve farmers' practice



In human and animal nutrition research, all studies providing more information on changes in the mineral composition of food (vegetables, fruits) and fodder over the last couple decades are of value in the aim of improving health.

From the soils viewpoint, determination of exchangeable K by soil extractants, as a measurement of K availability in predicting K fertilizer response to crops has been used extensively and successfully on many soils. On soils containing 2:1 clay minerals which can both release and fix K at interlayer sites, however, the exchangeable K extraction method has proved unsatisfactory as a guide to K fertilizer recommendations. Prediction of crop requirements by chemical K extraction from soils also takes no account of the limitation of spatial availability of K to living roots which may be affected by physical and chemical soil factors such as low pH, drought, compaction or salinity as well as by plant factors including crop species or genotype. From this complexity of factors relating to potassium availability including soil extraction, clay mineralogy, weather, crop species and genotype, root distribution within the soil profile etc, we suggest that there is a need for a reappraisal for the estimation of K availability.

Fig.6 Required interactions between scientists, agrochemical industry and farmers including the extension service to improve farming practice



Much is already known about the behaviour of K in soils and plants (see "Potassium in soils: present knowledge" and "Potassium in plants: present knowledge"), but in general, on a global scale this information is not well passed on to or applied by the farmer. This big gap between scientific knowledge and its lack of use by farmers has to be bridged by better and more intensive knowledge dissemination as appreciated by Krauss (2003b) {see also Gill and Gill 2006). In order to achieve this aim there is an urgent need for a more responsible co-operation between scientists, the agricultural chemical industry and farmers together with involvement of an extension or advisory service (Fig. 6). Improving the interaction between these various bodies is particularly needed in a global world in which enormous progress in being made in basic sciences coupled with ever increasing demands on the farming industry to feed the rapidly and hugely expanding world population.

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