Potassium Role and Benefits in Improving Nutrient Management for Food Production, Quality and Reduced Environmental Damages, Vol. I

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5-7 November 2009

Volume I: Invited Papers

Potassium Role and Benefits in Improving Nutrient Management for Food Production, Quality and Reduced Environmental Damages

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IPI

IPNI

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Foreword

Worldwide, improving crop production is of increasing importance. With a rising population and steadily increasing demand of food per capita, India faces a particular challenge in meeting these needs and in improving its crop production. Moreover, increasing crop productivity is not just about the science of new technologies or management of crops as environmental sustainability is of vital importance. The complexity of the issues now faced make improving crop productivity a more challenging task. Managing inputs is a crucial issue. Water, fertilizers, crop protection inputs, and professional advice all need to be managed in the most effective way, not only because of their high costs, but also due to diminishing availability and increasing competition over use. Optimal use of resources, including land availability, is becoming more complicated as the rate of production increases, and requires enhanced science and improved application by farmers.

Food security is measured mainly by the production of cereals. However, as the income of the urban population increases, the demand for meat, vegetables, fruits and oil increase at a much faster rate than the production of cereals; the food of the poor - causing policymakers much concern. In recent years, as in other regions, growth rates of cereal production in India have decreased; a trend that must be reversed if food security is to prevail.

Balanced fertilization is an important tool in achieving improved crop production. The relatively low levels of potash fertilizer application in Indian agriculture leads to mining of potassium (K) from the soil, which results in a multitude of negative impacts, including preventing full utilization of applied nitrogen and phosphorus fertilizers that limit yields, decrease farmers' income, and hence jeopardize the future food security of the country. Indian farmers and their advisors need to adopt advanced tools for potash fertilizer applications, and state research institutes need to update K recommendations according to the latest scientific findings. We are encouraged that a number of papers included in these proceedings discuss the issue of efficient and balanced use of nutrients; others present latest findings on improving productivity in common cropping systems of the region. Several papers are focused on the quality aspects of agricultural produce, while others discuss issues of fertilization and environmental stewardship.

This publication, which is a result of the IPI-OUAT-IPNI International Symposium on “Potassium Role and Benefits in Improving Nutrient Management for Food Production, Quality and Reduced Environmental Damages”, which took place on 5-7 November, 2009 in Bhubaneswar, Orissa, India, contains all voluntary papers that were presented in the Poster Sessions at the event. The journal; Plant and Soil accepted nine invited papers from the Oral Presentation sessions at the symposium for publication and, with the journal's permission, these are included here. The proceedings are intended to provide the reader with up-to-date knowledge of aspects related to nutrient management in Indian and South Asian agriculture, as well as their application for wider audiences, with a particular emphasis on potassium.

We thank Dr. MS Brar and Dr. SS Mukhopadhyay for editing this volume.

Hillel Magen
Director, IPI

Adrian Johnston
Vice President, IPNI

Foreword

India has achieved foodgrain production of 234 million tons (the highest quantity achieved so far), but set a target of 276 million tons within the next 10 years, which has to be doubled to 450 million tons by 2050 to feed her burgeoning population. The situation is same for all Asian countries, which are home for more than four billion people. Apart from foodgrain production, agriculture is stressed to produce more fruit, more fibre, more bio-fuel, and more amount of industrial raw materials. This stress, if seen at the backdrop of declining per capita availability of cultivable land and renewable fresh water resources and a ever-increasing threat of global warming and increasing uncertainty of climate is truly worrisome. In the past decade, there was a strong demand of food and bio-fuel, which would likely to rise further as nations come out of recession. Together, they will put more pressure on scarce natural resources, and threaten to further accelerate in the extent and severity of the human-induced soil degradation (1.94 billion ha globally and increasing at the rate of 5–10 million ha annually).

Editors of Nature in 2009 identified seven parameters: climate change, ozone depletion, ocean acidification, biodiversity, freshwater use, the global nitrogen and phosphorus cycles, and change in land use for the biophysical processes that determine the Earth's capacity for self-regulation. They warned that we must stay within the boundaries in order to avoid catastrophic environmental change. Each one of these global issues are rooted in agriculture, which highlights the urgent need of reorienting our agricultural research to focus on fundamental issues of improving quality of ecosystems services and the environment. This is not an easy task, seeing that large number of our researchers, especially in developing countries, engaged themselves into nutrient management research in its most primitive form. At the same time our farm service providers lack skills and power to communicate the farmers need of balanced use of nutrients in environmentally sustainable manner, and for choice of right crop, and right nutrients and right management practices for a profitable farming. Yes, farming in these countries can be profitable, if these issues are taken care of. It is important to remember that fertilizer subsidy can’t continue for long and rising food prices can become the single most threat to peace. Therefore, we need to be innovative in our approach in understanding agricultural production system alongside socio-economic compulsions to overcome current crisis in agriculture. Our new tools like newer models, breakthroughs in genomes, advancements in understanding in root system in crops to name a few, and a synergy between nanotechnology, biotechnology and information technology must be strategically incorporated into our nutrient management research to address these issues. It is also important for the nutrient-management researchers to use concepts like Fuzzy logic and remote sensing techniques to transfer experimental field results to the farmers’ fields.

Similarly, response of nutrient application is never linear, and there is a need to interpret it by applying concepts of the non-linear dynamical system, so that proper crop-specific protocol is developed in the interest of farmers, and climate related constraints and stress can be addressed to facilitate profitable farming. I will also strongly advocate the use of precision farming in nutrient management research so that farmers can use inputs judiciously for most economical and profitable farming while protecting the environment and scarce natural resources.

I congratulate IPI and IPNI for holding this important global event in India and highlighting the plight of nutrient management, especially for populous countries like China, India, Bangladesh, Pakistan, and Sri Lanka. I am sure, IPI and IPNI will steer farming into new millennium's challenges for the future as well.

18/4/2011

(JS Samra)
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Preface

The International Symposium entitled, “Potassium Role and Benefits in Improving Nutrient Management for Food Production, Quality and Environmental Damages” was held at the Orissa University of Agriculture and Technology, Bhubaneswar-751003, India from 5-7 November 2009. During the symposium, 34 invited speakers presented papers covering different aspects of balanced fertilization. Present volume consists of 30 papers including 9 papers published earlier in the Plant and Soil (Vol. 335; 2010) journal. The 'Extended Abstracts' of papers that were presented by the volunteered participants during the symposium were already published in the companion Volume II.

The symposium treated role of potassium nutrition to plants holistically – from fundamental aspects (Romheld; Kirkby; Lambers) to outreach activities (Raviprasad and Adhikari), and from pedosphere to human health (Stein; Bhaskarachary). It covered importance of soil fertility mapping through GIS (He et al.), role K plays in alleviating water stress (Srinivasarao et al.; Rengel), salt stress (Singh et al.), acid or iron stress (Panda; Mitra et al.), and climate change (Clair and Lynch; Snyder and Johnston). Potassium's contribution to quality of the produces (Lester et al.; Mitra and Dhaliwal; Ebert) was given due emphasis. Potassium does not work in isolation, but improves use efficiency of many other nutrients both for production of crops and environmental safety (Zhang et al.). Ecosystems apart from field crops and horticulture also get benefitted from K applications. Two papers – one on forest ecosystem (Smethurst), and other on grass rotation (Oborn et al.)-dealt with that. Three papers wrapt issues of demarking of the K deficient sites in some areas that were earlier thought well-supplied with available K (Buresh et al.; Sanyal et al.; Benbi and Brar). These sites could be chosen for laying K-response demonstrations for farmers. This volume includes seven papers that analyzes situation of K-centric balanced fertilization in soils with focus on the geographic regions within South Asia (Timsina et al.), especially India (Samra and Sharma; Subba-rao and Reddy; Satyanarayana and Tewatia; Singh and Bansal), Pakistan (Ahmed and Mian), and Bangladesh (Islam).

Editorial Board places on record deep sense of gratitude to the International Potash Institute, the International Plant Nutrition Institute and the Orissa University of Agriculture and Technology for organizing and bearing financial liability of the august event. We are also indebted to the Indian Council of Agricultural Research, Fertilizer Association of India, Bangladesh Fertilizer Association and Pakistan Agricultural Research Council for their sponsorship. We thank NBARD for partly financing publications of the proceedings. We are grateful to His Excellency Shri MC Bhandare, Honorable Governor of Orissa for

gracing the Inaugural Function. We acknowledge with thanks for the kind support extended by Dr. N Panda, Chairman, WODC and Prof. DP Ray, Vice-Chancellor, OUAT. We admire Dr. D Jena for untiring work as Organizing Secretary, and for providing leadership. We are obliged to the chairpersons of the sessions for making our work plausible. We are indebted to the authors for copy right transfer and for allowing us to publish their papers.

Editors

Contents

Food security - Indian scenario

JS Samra • PD Sharma

Abstract India is continually faced with the problem of increasing food production to feed its teeming millions. Achieving targets is a formidable challenge in the backdrop of declining factor productivity in agriculture since 90s. The National Agricultural Policy recognizes efficient conservation and management of natural resources as one of the essentials for higher productivity and agricultural growth. Along with food security, nutritional security is to be provided to about one-fifth of Indian population suffering from malnutrition problems.

The declining fertilizer response for the last thirty years (from 13.4 kg grain kg^{-1} nutrient in 1970 to 3.7 kg grain kg^{-1} nutrient in 2005 in irrigated areas) necessitates change in the fertilizer-use pattern. We need to adopt balanced (including micro and secondary nutrients) and integrated nutrient management for higher productivity and profitability. The supplies of organic manures, biofertilizers, micro and secondary nutrients and soil amendments have to be augmented to have integrated nutrient management on a sound footing. To have sustained and adequate supplies of fertilizers, appropriate policy initiatives are required to restore the health of the fertilizer industry and make it a vibrant sector. The indigenous sources of nutrients like rock phosphate (P), phosphogypsum (S) and waste mica (K) need to be exploited to reduce dependence on imports for fertilizers.

The availability of adequate irrigation water is going to be uncertain in foreseeable future due to growing competition from other sectors and slow pace of development of irrigation potential. The focus, therefore, requires to be given on enhancing surface and ground water-use efficiencies and use of waste waters. The rainfed areas covering two-third of cultivated area and contributing 40 percent of food merit special attention. The interventions required for higher productivity in the areas are, rainwater harvesting, micro-irrigation, integrated nutrient and pest management, and choice of suitable crops (especially hybrids of maize, pulses and oilseeds). The amelioration of about 2-3 m ha of salt affected lands and 10 m ha of acidic lands should be taken on priority to increase food grain production by about

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25 million tonnes per annum. Appropriate soil and crop management practices need to be evolved to face the challenge of climate change.

Keywords Climate change • fertilizer response • integrated nutrient management • land degradation • water management

Introduction

India has achieved remarkable growth in agriculture, raising food grain production from 83 mt in 1960-61 to 231 mt in 2007-08. The achievement made country self-reliant in food grains by mid 80s and surplus for exports by 90s. However, the country is continually faced with the challenge of keeping pace with the demands for food of ever-growing population. The population is growing, presently, at the rate of 1.7 percent adding 20 million people per annum. The demand for cereals, pulses, oilseeds and sugarcane has been estimated to be about 262, 19, 54 and 345 million tonnes, respectively by 2020 compared to 193, 14, 35 and 262 million tonnes for the base year 2004-05 in the country (Table 1).

Table 1 Demand projections for various food products in India (mt)

Commodity	Base year (2004-05)	Projection 2020-21
Cereals	192.8	262.0
Pulses	14.2	19.1
Foodgrains	207.0	281.1
Milk and milk products	91.0	141.5
Egg (number billion)	44.1	81.4
Meat	6.0	10.9
Fish	5.9	11.2
Edible oilseeds	35.5	53.7
Vegetables	90.6	127.2
Fresh fruits	52.9	86.2
Sugar in terms of cane	262.3	345.3

Source: Chand 2007

The projected demands for other food items are also high. Achieving desired food targets is a challenging task, seeing the trend of stagnation or deceleration in the growth of Total Factor Productivity in agriculture since 90s, especially in the Indo-Gangetic Plains (Murgai 2000; Singh 2003; Kumar et al. 2004). The required growth rates per annum for cereals and pulses (2%), oilseeds (6%) and sugarcane (0.6%) to meet the projected demands are much higher than the realized growth rates for the last ten years (Chand 2007). There was depression in rates of production and productivity of major crops including pulses and oilseeds

(Anonymous 2004a). The slowdown in growth of food grains production notably after mid-nineties posed a virtual threat to food security in the country. The stagnating productivity got reflected in falling agricultural growth rate, reaching about 2 percent during Tenth Plan period (2002-07). The National Agricultural Policy identifies food security as one of the major challenges and aims to attain annual growth rates in excess of 4 percent over the next decades. As high growth of non-agricultural sector has not brought about any significant improvement in the socio-economic conditions of rural people, an inclusive higher growth in agricultural sector is the hallmark of agricultural policy of the Indian government. It envisages conservation and efficient management of natural resources amongst development of horticulture, livestock, fisheries, food processing and marketing infrastructure etc in rural areas. The Government of India has recently launched several initiatives including National Rainfed Area Authority (2006), Centrally Sponsored Scheme of Micro-irrigation (2006), National Agricultural Development Scheme (2007), the National Food Security Mission (2007) and *Rashtriya Krishi Vikas yojana* (RKVY) to have an increased and equitable agricultural growth. The primary objective of National Food Security Mission is to increase production and productivity of wheat, rice and pulses by focusing on districts having high potential for productivity gains. A number of technologies have been identified to minimize the yield gaps of 40-100 percent between experimental farms and farmers' fields (ICAR 2007). The new initiatives will also go a long way in fulfilling the United Nations Millennium Development Goals of Eradicating Extreme Hunger and Poverty in the Asian region.

Food security implies availability of adequate food to people to meet their dietary and nutritional needs for a healthy and productive life. More than one-fifth of Indian population, especially the rural families living below the poverty line, is still undernourished and suffers from protein-energy-trace elements-malnutrition syndrome. Although the notable increase in the production of fruits, vegetables, milk, eggs and fish (Anonymous 2009) may have improved the nutritional profile of the people to some extent, there is need for bio-enrichment of food grains with micro-elements through application of fertilizers to address widespread malnutrition problem.

Managing soil health

The impaired soil health is often cited as one of the reasons for stagnation in crop productivity (Sinha et al. 1998). The inadequate and imbalanced nutrient use coupled with neglect of organic manures has caused multi-nutrient deficiencies and organic carbon reduction in Indian soils. The deficiencies are becoming more critical for sulphur, zinc and boron. In early 1990s, about 130 districts were deficient in sulphur, the number today is over 240. About 47 million ha of area representing major cropping systems in the country is deficient in sulphur. Seeing the widespread deficiency, sulphur is being recognized as the fourth major plant nutrient in the country. The estimated gap between requirement and additions of S is about I million tonnes presently and is likely to be doubled within few years to meet targeted levels of production. The zinc deficiency is rampant in alluvial soils of the Indo-Gangetic plain, black soils of the Deccan Plateau and red and other associated soils. The boron deficiencies are showing up in red, lateritic and calcareous soils of Bihar, Orissa and West Bengal. The increased mining of soil potassium seems to be a cause of more rampant decline in rice yields compared to wheat in the Indo-Gangetic Plain, as revealed by the analysis of data pertaining to rice-wheat cropping system from 24 research stations in IGP (NAAS 2006). The limiting nutrients not allowing the full expression of other nutrients lower the fertilizer responses and crop productivity.

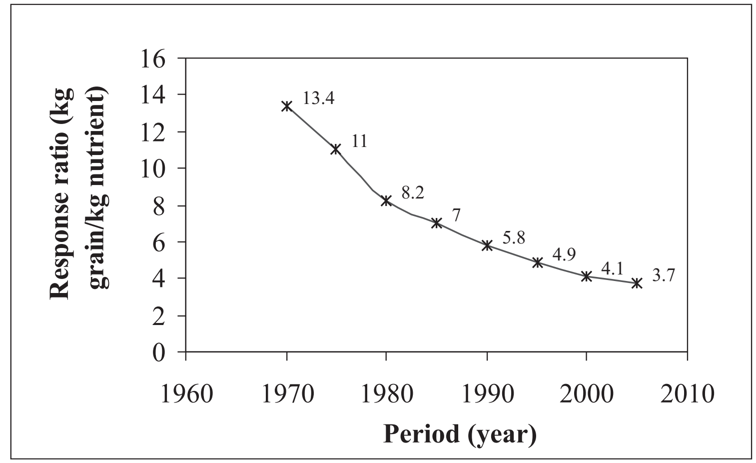
Declining fertilizer response

A decline in partial factor productivity of fertilizer has been revealed at country level, having related food grain production and fertilizer consumption for the last four decades (NAAS 2006). The response ratio was around 6 kg grain kg^{-1} nutrient for the last three decades. The picture on fertilizer responses was, however, made still more clear by relating the food grain production and fertilizer consumption for irrigated areas only consuming major share of the fertilizers. It was also appropriate to take out the increase in fertilizer consumption due to increase in irrigated area per se (increase from 30 m ha in 1970 to 56 m ha in 2005) from the total fertilizer consumption for the irrigated areas during this period. The more realistic fertilizer response ratios were, therefore, calculated employing the chain rule of partial differential calculus (Biswas and Sharma 2008a). The overall fertilizer response in irrigated areas of the country has decreased nearly three times from 13.4 kg grain kg^{-1} NPK in 1970 to 3.7 kg grain kg^{-1} NPK in 2005 (Fig. 1). The Individual nutrient ratios in respect of N, P and K also followed the same trend (Fig. 2). While only 54 kg NPK ha^{-1} was required to produce around 2 t ha^{-1} in 1970, around 218 kg NPK ha^{-1} are being used presently to sustain the same yield (Fig. 3). The declining fertilizer response since 70s is, therefore, a matter of great concern. The fertilizer input has been the mainstay of food production in India, contributing about 50 per cent towards crop productivity over the last 35 years.

Integrated balanced nutrient management

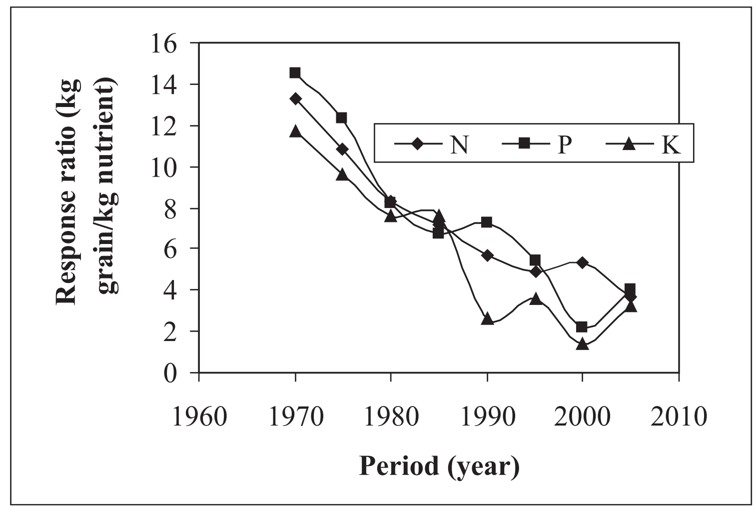
The Integrated nutrient management encompassing conjunctive use of chemical fertilizers including secondary and micronutrients, organic manures, composts / vermicomposts, bio fertilizers and green manures is the most ideal system of

Fig. 1 Fertiliser response of foodgrain crops in irrigated areas in India



(Source: Biswas and Sharma 2008a)

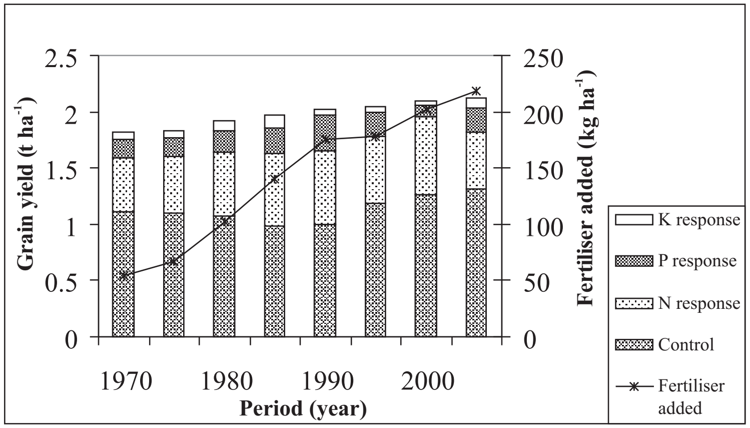
Fig. 2 NPK responses of foodgrain crops in irrigated areas in India.



(Source: Biswas and Sharma 2008a)

nutrient management. The system maintains soil health, enhances nutrient-use efficiency and yields and reduces cost of cultivation. Its usefulness has very well been demonstrated by the All India Co-ordinated Research Project on Long Term Fertilizer Experiments of ICAR running since 1970 (Samra 2006). The application of nitrogen alone gave very low use efficiency. The response increased

Fig. 3 Contribution of fertilizer NPK towards food grain production in irrigated areas in India.



(Source: Biswas and Sharma 2008a)

with the application of phosphorus along with nitrogen, but its reduction with time was again evident in the absence of potassium. The response got stabilized at a higher level only with the balanced application of NPK. Further improvement in the response could not be realized merely with the addition of higher amounts of chemical fertilizers. The addition of organic manure along with chemical fertilizers was required for obtaining such an effect. The continued additions of NPK fertilizers at higher rates without organic manure caused deficiencies of secondary and micronutrients. The deficiencies of S and Zn and consequent drop in the response level were noticed at some places that omitted S and Zn from the fertilization schedule. The site-specific nutrient management gave, on an average, annual grain productivity of 13.3 t ha^{-1} of rice-wheat at 10 locations across the Indo-Gangetic Plain (Tiwari et al. 2006). The extra net returns over the farmers' practice were Rs 20,530 with a benefit:cost ratio of about 5.0.

Ensuring adequate supplies of fertilizers

The availability of fertilizers on a sustained basis is essential for food security and overall growth in economy. To ensure fertilizers at affordable prices to the farmers, the subsidy/concession on them is an integral part of Government policy. The country will require about 45 mt of nutrients to produce 300 mt of food grains for about 1.4 billion population by 2025. Therefore, the fertilizer industry is required to augment fertilizer production substantially from the present level of about 23 mt of nutrients to keep pace with the food demands of the country. This looks to be unlikely, given the prevalent non-conducive policy environment for investments

in the fertilizer industry. There have been virtually no significant investments in urea and phosphatic sectors for the last ten and seven years, respectively in the industry. The continued stagnation in capacity and investment has affected adversely the production of fertilizers in the country. The country had been importing increasing quantities of fertilizers to meet the demands, the figures being 7.0, 3.0 and 4.4 mt of urea, phosphatic and potassic fertilizers, respectively for 2007-08 (Fertilizer Statistics 2007-08). The import dependence has, thus, risen significantly with 30 % dependence in nitrogenous sector, 90 % in phosphatic sector and 100 % in potassic sector. The import of fertilizers is, obviously, causing burden on the state exchequer.

One of the reasons for the stagnation in fertilizer industry is the pricing mechanism of the fertilizers under subsidy regime that leaves only thin margins for the industry. The returns to fertilizer industry are capped and efficiencies are mopped up to reduce subsidy bill. The delayed disbursement of subsidy further adds to the woes of the fertilizer industry. The subsidy is provided to farmers by charging only part of the delivered cost of the fertilizers at farm gate level by fixing MRPs. The government since 2002-03 to keep the fertilizers at affordable price to the farmers has not increased the MRPs of urea. The current MRPs are even less than 16 % of the delivered cost of the fertilizers. As delivered cost of the fertilizers has been escalating due to sharp increase in international prices of fertilizer inputs and finished fertilizers, the subsidy bill has been rising unusually in the recent years. It has swollen from Rs. 11,013 crore in 2002-03 to more than Rs. 100,000 crore in 2008-09. The Government is finding it difficult to cope up with the rising subsidy bill. There is need for rationalization of the existing subsidy regime that protects the interests of fiscal planning, fertilizer industry and farmers.

The fertilizer industry requires capacity enhancement through revamp, expansion, new plants and joint ventures abroad. A number of old Naphtha and fuel oil based plants (present capacity being 26 %) with about 2.5 times more cost of production compared to gas based plants need to be phased out. These plants have lot of subsidy burden on the Government. To have committed supplies of natural gas to the gas based plants, the fertilizer sector should have priority allocations of the natural gas. Although the supplies are going to improve soon with the production from the Krishna-Godavari Basin fields, the demand is likely to outstrip supplies. Given the production constraints in the country, the joint ventures abroad seem to be a desirable strategy. Such ventures have already been initiated with Morocco, Jordan, Senegal, Oman and UAE.

To promote balanced fertilization, we need to move to nutrient based pricing and subsidy and fortification/coating of fertilizers with micro and secondary nutrients. The move would broaden the basket of fertilizers and enable fertilizer use as per soil and crop requirements. The fully water soluble/liquid fertilizers suitable for fertigation of horticulture, plantation, vegetable, floriculture and other high value crops need to be evaluated and popularized. These fertilizers hold great promise in the context of micro-irrigation being expanded to 69 m ha in subsequent Plan periods. The fertigation results in saving of the fertilizers by about 40 percent. The fertilizers being imported, presently, are costly and require to be produced by the Indian fertilizer industry. We need to encourage production and use of SSP to correct widespread sulphur deficiency in soils besides serving as a source of phosphorus. It is also suitable for making fertilizer mixtures and customized fertilizers. The regular and higher rate of concession would incentivise its production and use. Presently, only 16 fertilizers are covered under subsidy/concession scheme and a large number of other fertilizers including the products containing secondary and micronutrients are outside the ambit of subsidy policy. It would be in the interest of the Indian farmer, if these fertilizers were covered under the concession/subsidy scheme.

We should utilize all indigenously available nutrient sources to reduce dependence on import of fertilizer raw materials/ intermediates and finished products. There are good reserves of low grade rock phosphate (160 million tonnes) and potassium bearing mica in the country. The reserves uneconomic for exploitation as fertilizers, could be used for production of enriched manures containing P and K through co-composting. Phosphogypsum, a by-product of phosphoric acid based fertilizer industry containing 16 % S and 21 % Ca, could serve as a potential source of sulphur and calcium to crops. About 7 million tonnes of phosphogypsum are generated per annum by the fertilizer industry. The product has a potential to supply about 1 million tonnes of sulphur and 1.4 million tonnes of Ca annually. All the coarse textured, acidic and sodic soils low in S and Ca would benefit from its supplementation. Its agronomic value has been tested on a variety of cereal, oilseed and pulse crops under varied agro-climatic situations (Biswas and Sharma 2008b).

Augmenting supplies of organic manures

To have Integrated Nutrient Management System (IPNS) on a sound footing, we need to augment the supplies of organic manures. The availability of organic manures comprising rural and urban composts, farm yard manure, vermicompost and other materials is around 385 million tonnes per annum (DAC 2009) against the moderate requirement of about 900 million tonnes per annum (assuming addition @ 5 tonnes ha^{-1} on a gross cropped area of 185 m ha) at the country level. The supplies could be augmented to some extent by composting large amounts of urban and agro-industrial wastes. About 57 million tonnes of urban solid wastes generated per annum have a potential to provide 8 million tonnes of good quality compost in the country. Besides, a variety of agro-industrial wastes like press mud, spent wash, poultry litter and fruit and vegetable waste could be recycled and converted into valuable manure. There is need to develop technologies for the

production of cheap and quality composts. Also, appropriate quality standards should be established for composts to ensure their safe use in agriculture.

Promoting bio-fertilizers

Biofertilizers being cheap and eco-friendly sources of nutrients are important component of integrated nutrient management system. The production of biofertilizers is still low, being around 20,000 tonnes per annum against the installed capacity of 67,162 tonnes per annum of 164 biofertilizer units in the country (DAC 2009). The production is skewed as well, with 90 % of production confined to southern and western parts of the country. The low popularity and use of bio-fertilizers is ascribed to their poor quality linked with inappropriate strains for a given soil and climatic situation and inefficient production technology (Singh et al. 1999). A survey by ICRISAT (Singletone et al. 1996) has revealed 90 % of biofertilizer samples lacking the required Rhizobia count for effective performance. Greater research and development efforts are required to increase shelf life of biofertilizers by way of isolating location-specific strains, better production technology avoiding contamination and better storage and handling. The liquid cultures containing cell protectants maintain high microbial numbers and promote the formation of resting cells like cysts and spores having resistance to abiotic stresses. Even after one year of storage, the liquid media maintained higher cell count of Rhizobium, Azospirillum and P-solubilising Bacillus megaterium (Rao 2008) compared to commonly used lignite carrier. The region and crop specific consortia of biofertilizers (combining Azotobacter, Azospirillum, Phosphate solubilizing bacteria, Rhizobium and Plant Growth Promoting Rhizobacteria) should be developed to popularize biofertilizers.

Developing nutrient-use efficient cultivars

The development of crop cultivars having ability to thrive well even under low fertility situations through biotechnological manipulations is an interesting area of research. The manipulations could be thought in terms of increased root growth and its changed architecture, increased secretions of enzymes and organic acids by root tips and symbiotic relationships with mycorrhizal fungi to have mobilized more nutrients by roots. The root exudates bring sparingly soluble nutrients into soil solution and enhance their acquisition by roots. The nutrient use efficient cultivars would affect considerable savings on costly fertilizers and mitigate micronutrient/trace element related malnutrition.

Nanotechnology for slow release fertilizer

The nanotechnology promises slow release fertilizers (nanoporous zeolites) and soil quality and plant health monitoring systems (nanosensors). The new products and tools would go a long way in managing soil fertility and enhancing crop productivity.

Ensuring nutritional security

The dietary inadequacies of Zn, Fe, I, Al, Cu, Mn, Co etc. and associated malnutrition / health disorders in humans and animals are linked with deficiencies of these elements in soils and foods. Over one billion people in South Asia still suffer from protein-energy-trace elements-malnutrition syndrome (United Nations 1992). The problem is more serious in young children, women of child bearing age and livestock. The trace element deficiencies could be geogenic in nature depending on mineral and soil composition or induced due to increased mining of nutrients under intensive agriculture. The Zn deficiency has become a big public health issue in India and is second in importance to Fe. It is assumed that around 25 % of Indian population is under risk of Zn deficiency related problems. The Zn content of crops grown on Zn deficient soils is generally lower than on the Zn sufficient soils. The analysis of about 250,000 soil and 25,000 plant samples collected from different states in India has indicated that 48 % soil and 44 % plant samples were deficient in Zn (Singh 2007). The dietary intake of 0.2- 0.3 mg Zn day^{-1} is regarded as deficient. Its deficiency impairs the immune system and increases the incidence of infectious diseases such as diarrhoea and pneumonia. It also causes dwarfism, hypogonadism, anemia, geophagia, anorexia, skin lesions, rough and dry skin and loss of taste etc. A study in Haryana on 283 pregnant women has showed 65 % of them to be deficient in Zn based on low serum Zn concentration (Pathak et al. 2008). The Zn deficiency related disorders like parakeratosis disease, associated with bone and joint disorders and thickening of skin, has been reported from Panjab and Haryana in animals feeding continuously on forages deficient in Zn (Vasudevan 1987). Likewise, wool-shedding syndrome in Corriedale sheep was observed at the Central Sheep Breeding Farm, Hissar due to Zn deficiency (Mandokhot et al. 1987).

The high incidence of Zn deficiency in Indian population is primarily due to more consumption of cereal-based foods and less of animal based-foods or pulses. The rice and wheat, constituting major staple foods in India, contribute about 60-70 % of daily calorie intake. The cereal grains are not only low in Zn, but also contain antinutritive compounds like phytates which reduce bio-availability of Zn. Growing of cereals on Zn deficient soils will further reduce the availability of Zn in grains. This has been very well demonstrated by a study in Central Anatolia, Turkey facing problem of Zn-deficiency. The Zn concentration in grains of 54 wheat cultivars grown on a Zn deficient soil averaged 9 mg Zn kg^{-1} compared to 26 mg Zn kg^{-1} on normal soils (Cakmak 2008). The application of Zn fertilizers on

these soils has increased substantially the wheat yields and Zn content in grains. The consumption of Zn containing fertilizers has increased from nil in 1994 to about 400,000 tonnes per annum in Turkey. The economic benefits in terms of crop productivity and human health enhancement are enormous. The Anatolian experience, therefore, merits its replication in other Zn-deficient areas to address public health while improving crop production. Zinc is one of the nutrients depleted significantly under intensive agriculture, especially in rice-wheat cropping sequence, in India (Tandon 1995) and requires its replenishment through fertilizers for food and nutritional security.

The iron malnutrition is a problem in many parts of the world including India (United Nation 1992), where poor people depend largely for their food on cereals containing low iron. The iron deficiencies are associated with anemia, fatigue, nervousness, reduced appetite, lower wait gain, sore tongue and memory loss etc. The iron deficiencies have been reported in livestock of north-western Rajasthan and sheep and goats in West Bengal (Sarkar et al. 1992 a, b). The deficiencies of Cu, especially in sandy soils or soils having large content of organic matter, have also been reported to affect crop productivity and human health in India. Its deficiency causes defective melanin synthesis leading to leucoderma (vitilogo), osteoporosis, arthritis, infertility and cardiovascular disorders etc in humans. Its deficiency caused depigmentation of hair and skin in buffaloes in India, Pakistan and Indonesia (Randhawa 1999; Sinha et al. 1976). In South Australia and New Zealand, the cows grazing on Cu deficient lands suffered from heart failure Falling Disease.

Augmenting water resource

The irrigation sector is the largest consumer of fresh water (about 83 %) in the country. Its share, however, is going to decline to 72% and 68% in 2025 and 2050, respectively (MoWR 1999) in the wake of growing competition from the industrial and domestic sectors. The per capita water availability in India has reduced to 1820 m^3 in 2001 compared to 5200 m^3 in 1950. It has now declined to below 1700 m^3, the limit considered as cutoff for being water stressed, and would be less than 1000 m^3 per capita per year for about two-third of population by 2050 (Planning Commission 2002). The per capita water availability in India is very low compared to 25,708 m^3 in Australia and 10,837 m^3 in USA. The future gains in agricultural productivity of the country are, therefore, going to be determined by proper development and utilization of surface and ground water resources.

India could meet its required irrigation potential of about 180 million ha from major and medium irrigation sources (58.5 million ha), minor irrigation sources (81.5 million ha; 64.1 million ha as ground water and 17.4 million ha as surface water) and inter-basin transfer of river waters (35 million ha). The achieved irrigation potential of about 56 million ha is grossly inadequate covering only 40 % of total arable area. There is continued gap between the assessed irrigation potential and actual irrigation potential put to use in different states (CWC 2007). As execution of major irrigation projects takes long time and inter-basin water transfer remains a debatable subject, the augmentation of water resource in the short term could be viewed within the perspective of conservation of existing water resources through better water management (Chowdary et al. 2005). A number of measures like harvesting of rain water in small storages, controlling seepage from canals, efficient water distribution systems, additional ground water development through artificial recharge, conjunctive use of surface and ground waters, use of poor quality and waste waters and micro-irrigation could augment water resource to a significant extent.

Rain water harvesting

India receives 400 M ha-m of rainfall per year. Of this, only 69 M ha-m are available as surface flow and 43 M ha-m as ground water. Therefore, only 29 percent of annual precipitation is used and rest is lost as runoff to sea or as water vapour to atmosphere. The potential exists for harvesting nearly 24 million ha-m of rainwater in small-scale water harvesting structures in various rainfall zones (Table 2).

If stored properly, about 30 percent of it (7million ha-m) could be available as pre-sowing and protective irrigations for about 95 million ha area under Rabi crops. The intervention promises additional food grain production of about 60 million tonnes per annum.

Table 2 Estimated rainwater harvesting storage potential in different rainfall zones, India

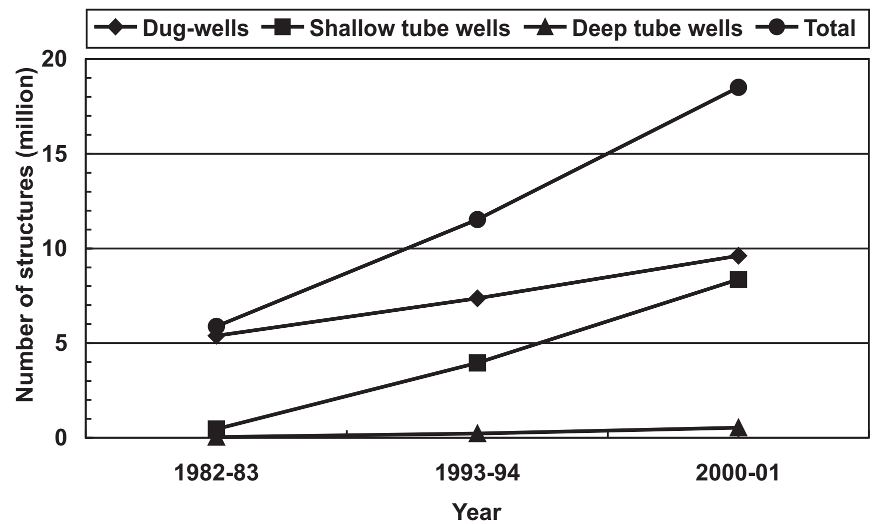
Rainfall zone (mm)	Area (m ha)	Rainfall for effective surface storage (%)	Harvestable runoff in water harvesting structure (m ha-m)
110-500	52.1	5	0.8
500-750	40.3	6	1.5
750-1000	65.9	7	4.0
1000-2500	137.2	6	14.6
> 2500	32.6	4	3.3
Total			24.0

Source: CSWCRTI 2007

Checking fall in water table

The groundwater is being increasingly depleted in Central Punjab, Haryana, Western Uttar Pradesh, Rajasthan, Tamilnadu, and West Bengal due to its over drawl. The increased ground water abstraction (Fig. 4) has been prompted by the availability of free or subsidized power and pumpsets in the rural areas since eighties. The decline in ground water used for irrigating over 60 % area poses a threat to food security besides entailing mounting over head costs to the farmers in deepening their wells, installing submersible pumps and incurring more power to lift water from increasing depths. The hard hit is the marginal and small farmers, whose shallow/dug wells would go dry as the water table goes deeper with over drawl. For equitable resource use, we should have clearly defined property rights

Fig. 4 Growth of Groundwater abstraction (Source: CGWB 2007)



to surface and ground waters. Presently, a land owner is entitled to draw any amount of ground water even if no water is left for others in the area. The Central Ground Water Board has drafted a Model Bill (CGWB 2007) for adoption by the states to ensure sustainable and equitable development of ground water resources. The bill entails registration of bore well owners, statutory permission to sink a bore well, restriction on the depth of bore wells and creation of a ground water regulation body etc. The recharge of groundwater through appropriate interventions is also assuming great significance in the country. There have been spectacular increases in ground water table (0.2-2m) in well-managed watersheds in different parts of India (Table 3). The conventional methods of augmenting

Table 3 Effect of watershed interventions on ground water recharge in different regions, India

Watershed	Surface storage capacity Created(ha -m)	Observed rise in ground water table(m)
Bazar-Ganiyar (Haryana)	79.0	2.0
Behdala (H.P.)	18.0	1.0
Bunga (Haryana)	60.0	1.8
Chhajawa (Rajasthan)	20.0	2.0
Chinnatekur (A.P.)	5.6	0.8
GR Halli (Karnataka)	6.8	1.5
Joladarasi (Karnataka)	4.0	0.2
Siha (Haryana)	42.2	2.0

Source: CSWCRTI 2007

ground water recharge like percolation ponds and check dams have found a major place in all watershed development programmes. However, the new recharge techniques like recharge pits and shafts and injection wells etc need to be evaluated for best results.

Use of waste water

India generates about 18.4 million M^3 of wastewater per day as sewerage and industrial effluents. The waste waters are, generally, used for irrigation on agricultural lands for the cultivation of vegetables, fruits and other food crops. As hardly 20% of waste water is treated in the country (Patnakar 2001), the effluents are, generally, loaded with prohibitive levels of heavy metals and toxic compounds (Tiwana et al. 1987; Mitra and Gupta 1999; Brar et al. 2000; Khurana et al. 2003). The continued use of waste waters on agricultural lands increases the load of toxic substances, heavy metals and pathogenic microbes in soils, waters and foods (Brar et al. 2000) endangering human and animal health.

For safe use of waste waters, there should be strict enforcement of safeguards on their use as prescribed by the regulatory authorities. The effluents should be pre-treated to remove/reduce their toxic load. The effluent treatment plant of leather industries at Jallandhar, Punjab lowered significantly the concentration of chromium in the effluent from initial 21 ug mL^{-1} to 0.8 ug mL^{-1} (Brar et al. 2000). The pre-treated effluent is being used continuously for more than two decades without any adverse effects on soils and crops in Tamilnadu (Pushpavalli et al. 1999).

The high establishment and operational costs of waste water treatment plants are some of the constraints in their large scale use. The cost-effective methods

based on biological and soil-aquifer treatment approaches are, therefore, being advocated. The waste waters could also be used safely after their dilution with fresh water to contain the load of toxins within the permissible limits (Minhas and Samra 2004). Aquaculture based utilization of sewage water also seems to be an attractive proposition in high rainfall areas (Minhas and Samra 2004).

Enhancing water-use efficiency

The irrigation efficiency is low for both surface and ground waters. It requires to be enhanced from 35 percent to 60 percent for surface water and from 65 percent to 75 percent for ground water. Even an increase of 5% in irrigation efficiency could increase irrigation potential by 10-15 million ha. Losses in water conveyance system are normally 40-50 % due to leakage, seepage and evaporation. Lining of canals or distribution system is recommended where the availability of surface water is much less than the demand and exploitation of ground water is a costly affair. The adoption of pipe distribution system is recommended to reduce water loss in the distribution system. The improved on-farm water management through efficient irrigation scheduling, water application and choice of suitable crops and cropping systems matching available water supplies could go a long way enhancing the irrigation water use efficiency (Rao and Sinha 1991). The micro-irrigation promises further increase in water-use efficiency by 40-50% compared to surface irrigation.

Amelioration of degraded lands

The mounting anthropogenic pressure on land resources has left 31 percent of global land resource at the brink of ecological collapse (Eswaran et al. 2006). This is the land that has diminishing capacity for biomass production. A large proportion of this land belongs to rainfed regions. Amongst Asian countries, India and Thailand are the worst affected. Although the land degradation figures for India furnished by various agencies are at variance (varying from 53 to 188 million ha) due to differences in approaches, methodologies and criteria for assessment, the fact remains that large area is under degradation due to different degrading agents. Recently, the datasets on land degradation/wasteland available with different agencies have been harmonized in GIS environment for whole country. As per new estimates, 120.7 million ha constituting 36.5 percent of total geographical area are degraded in India due to soil erosion, salinity/alkalinity, soil acidity, Water logging, and some other complex problems (Table 4). The degraded soils with very low productivity do not contribute much to the national GDP. Enhancing productivity of these lands is central to the planning for food secure India, seeing little scope for horizontal expansion in the cultivated area in future. The arable area may rather diminish with the mounting pressure for good lands

Table 4 Degraded lands in India (M ha)

S.No.	Type of Degradation	Arable land (M ha)	Open forest (<40% Canopy) (M ha)
1	Water erosion (>10 t/ha/yr)	73.27	9.30
2.	Wind erosion (Aeolian)	12.40	-
	Sub total	85.67	9.30
3.	Chemical degradation		
	a) Exclusively salt affected soils	5.44	-
	b) Salt-affected and water eroded soils	1.20	0.10
	c) Exclusively acidic soils (pH< 5.5)	5.09	-
	d) Acidic (pH < 5.5) and water eroded soils	5.72	7.13
	Sub total	17.45	7.23
4.	Physical degradation		
	a) Mining and industrial waste	0.19	-
	b) Water logging & marshy lands (permanent) (water table within 2 mts depth)	0.97	-
	Sub total	1.16	-
	Total	104.28	16.53
	Grand total (Arable land and Open forest)	120.81	

Source: NBSSLUP 2008

from industrial and domestic sectors. The Planning Commission, Government of India, accordingly, envisages rehabilitation of 88 million ha of degraded lands in the next four plans period. There is need for proper land-use planning consistent with the prevailing socio-economic-environmental-market imperatives for sustainable management of land resources. The plans must be wedded to the strategies of diversification and integrated farming, seeking all round development of an area.

Eroded land

Soil erosion due to water and wind is the major cause of soil degradation affecting about 95 million ha area (Table 4). About 39% of total geographical area has soil erosion beyond the permissible rate of 10 t ha^{-1} yr^{-1} (Table 5). The area under severe soil erosion category of more than 40 t ha^{-1} yr^{-1} constituted about 11%. Some of the

Table 5 Area affected by potential soil erosion in India

Soil erosion (percent of Total Geographical Area)					
Moderate (10-15 t/ha/yr)	Moderate severe (15-20 t/ha/yr)	Severe (40-80 t/ha/yr)	Very severe (40-80 t/ha/yr)	Extra severe (>80 t/ha/yr)	Total (>10 t/ha/yr)
11.22	6.46	9.92	7.14	3.99	38.73

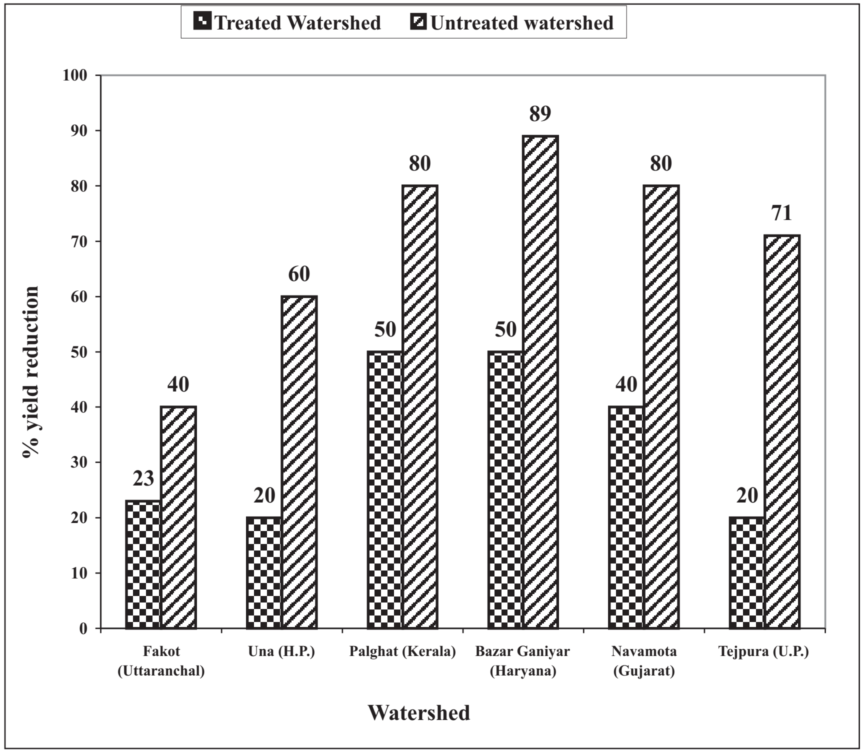
Source: NBSS&LUP 2008

Himalayan states were worst affected with more than one-third area falling in the category of severe soil erosion. The earlier studies (Singh et al. 1992) have also revealed serious problem of soil erosion in the north-western Himalayan regions, Siwalik Hills, Shifting cultivation regions of NEH, Western Coastal Ghats, ravines and black cotton belt of Peninsular India. The rates were quite high for Siwalik Hills (> 80 t ha^{-1} yr^{-1}) and shifting cultivation regions in NEH (>40 t ha^{-1} yr^{-1}). In quantitative terms, about 5.3 billion tonnes of soil are eroded in India at an average rate of 16.3 t ha^{-1} yr^{-1} (Dhruvanarayana and Ram 1983). While 61 percent simply moved from one place to another, nearly 29 percent were lost permanently to the sea. The remaining 10 percent were deposited in reservoirs reducing their holding capacity by 1 to 2 percent annually. About 8 million tonnes of plant nutrients were also washed away along with eroded sediments. The increased soil erosion taking away the fertile topsoil and forcing decline in crop yields (Yadav et al. 1993; Agnihotri et al. 1994) is, therefore, a biggest threat to food security. The adoption of appropriate soil and water conservation measures is essential for protecting the lands from accelerated soil erosion.

Watershed management in rainfed areas

Many model watersheds developed in different parts of the country by research institutes, government departments and non-governmental organizations have demonstrated their usefulness in conserving soil and water resources and ameliorating the socio-economic conditions of rainfed regions (Samra 2002**).** Some of the successful watersheds are Sukhomajri, Ralegaon Sidhi, Chitradurga, Fakot, Kothapally, Tejpura and Alwar. The severe drought of 1987 in the country has demonstrated the potentialities of watershed management as a drought mitigation strategy (Fig. 5). Accordingly, the programme was scaled up at the national level with larger public investments in National Watershed Development Program for Rainfed Areas (NWDPRA), Integrated Wasteland Development Project (IWDP) and many other initiatives supported by World Bank, DFID, DANIDA and SIDA etc. Over the last three decades, the Government of India has

Fig. 5 Effect of watershed management on drought moderation in 1987 (Source: Samra 2005)



treated 56.5 million ha of degraded lands at an expenditure of about Rs. 20,000 crores under watershed management programme.

The Fakot watershed in the Garhwal Himalaya has increased the total food production, cropping intensity and average family income during 20 years of its operation (Dhyani et al. 1997). The development of Salaiyur watershed in Coimbatore improved irrigation resource and crop diversification indices (Sikka et al. 2004). The management of Kokriguda watershed in Orissa reduced soil loss from 38.2 to 6.6 t ha^{-1} $year^{-1}$ and runoff from 37 to12 percent with yield increases of little millet and upland paddy by 15 and 38 percent, respectively (Patnaik et al. 2004). Similarly, The Rajiv Gandhi Watershed Mission in Madhya Pradesh brought about increase in irrigated area by 59 % and in agricultural production by 37 % in Kharif and 30 % in Rabi season. The ground water improved in over 3000 villages covered under the project.

The ICRISAT, Hyderabad has been developing community watersheds in India, to improve land productivity and livelihoods for poor people. The development of 150 community watersheds gave significant yield gains of 35-270 % in sorghum, 30-174 % in maize, 72-242 % in pearl millet, 28-179 % in groundnut and 97-204 % in sole pigeonpea (Dar 2007). The ICRISAT has carried out meta analysis of 311 watersheds in India in terms of efficiency, equity and sustainability benefits (Joshi et al. 2005). The mean benefit-cost ratio of watershed program in the country was quite modest at 2.14. The internal rate of return was 22 per cent which compared very well with rural development programs. The watershed programs generated enormous employment opportunities, augmented irrigated area and cropping intensity and conserved soil and water resources. The study concluded that the watershed program is silently rejuvenating and revolutionizing rainfed areas.

The rainfed areas covering two-third of cultivated area and contributing 40 percent of food merit special attention in terms of bridging the gaps in production technologies and resource allocations. The areas bypassed by the green revolution still have poor resource base and marketable surplus. The various interventions required for achieving higher productivity in the areas are, rainwater harvesting, micro-irrigation, integrated nutrient and pest management, choice of suitable crops (especially hybrids of maize, pulses and oilseeds), increased credits and crop insurance etc. The establishment of National Rainfed Authority in 2006 will go a long way in ushering in the required socio-economic-food security in the areas.

Bio-industrial watershed management

The economic and social benefits of watershed management could be upscaled further by bringing industry to the watersheds and transforming them to the industrial watersheds (Bali 2008). The new system would have the bio-produce processed and value added at the watershed level, thereby, bringing urban profits of industry and commerce to the rural poor. The watershed people through cooperatives or corporates should wholly or substantially own these bio-industries. Even the landless people of the watersheds would be partners of the bio-industry. The fresh or processed watershed produce will be sold directly to the consumers by these cooperatives, doing away with the middlemen. An industrialist or entrepreneur ready to invest for the bio-industry, should be acceptable provided the person provides 40 percent of share to the cooperative. The bio-industry would take upon itself the role of running the affairs of bio-industrial watersheds. It would arrange for grants from the Government for soil and water conservation works and build-up of infrastructure and credit from financial institutions for production purposes. It would develop backward linkages to provide production inputs like seeds, planting materials, fertilizers, manures, pesticides, drip / fertigation systems and technical know-how etc and forward linkages in finding markets and remunerative prices for the produce. The bio-industrial watershed management is different from the contract farming in the sense that it does not only focus on production and buy back of the produce, but takes care of natural resource conservation and protection also to have sustainable production.

It would be prudent to have all the Central and State governments' watershed management programmes converted into bio-industrial watersheds. There are a number of watershed level activities related to agriculture, horticulture, agro-forestry, livestock, fisheries, poultry, sericulture, mushroom farming, honey bee keeping and vermi-composting etc that could form agri-enterprizes for bio-industrial watershed development. We need to choose such enterprizes suiting to varied socio-economic-environmental conditions of different rural areas for greater livelihood, nutritional and environmental security. The operation of one thousand per annum capacity vermicompost bioindustry involving one hundred households of a watershed, could generate net income of about Rs 50 lakhs besides creating employment to rural households, especially women. There is growing demand for vermi-composting for high value fruit, plantation, vegetable and organically grown crops. The country with the existing vegetational wealth is capable of sustaining 150 million bee colonies, providing 1.5 lakh tonnes of honey. The value addition to the produce at the watershed level would fetch more income to the farmers while generating employment for 15 million rural and tribal families. Likewise, the mushroom farming is big livelihood generator in rural areas. The horticulture-based food processing industry under bio-industrial watersheds is going to offer immense economic gains and livelihood opportunities besides food and nutritional security to rural people. Horticulture is emerging as a single largest category in world agricultural trade accounting for over 20 percent of share in recent years. The great demand for fresh fruits and vegetables worldwide is stimulating international trade in horticulture in India. The Government has been spearheading horticultural development through National Horticulture Mission in providing suitable infrastructure in terms of handling, transportation, storage, markets, processing and value addition. India loses more than Rs 58,000 crores worth the agricultural produce due to lack of post-harvest and food processing infrastructure.

The bio-industrial watershed management system could be viewed on the parlance of Amul cooperatives in Gujarat, Kuppam vegetable farming and processing cooperative in Andhra Pradesh, Kokam fruit concentrate production cooperatives in Maharashtra and Goa, sugar mills co-operatives in Maharashtra and Gujarat, Leh Berry fruit concentrate production cooperative in Leh (J&K) and many other ventures in different parts of the country. As animals are essential

component of farming system in rural India, the bio-industry based on milk, poultry, wool, meat and other animal products could be a great success. The development of cold storage /cold chain to store and transport perishable produce to the markets at appropriate time to avoid distress sales should be part of the bio-industrial development programme.

The programme fits very well in the framework of various rural development schemes, including National Rural Employment Guarantee Act (NREGA), launched by the Government of India. The programme also has great promise in fulfilling the United Nations Millennium Development Goals (MDGs) of eradicating extreme poverty and hunger, promoting gender equality and empowerment of women and ensuring environmental sustainability. The greater institutional support to the programme through Government departments, financial institutions and *Panchayati Raj* Institutions would allow tapping of a multitude of potential benefits of the bio-industrial watershed management programme. The National Rainfed Area Authority established recently to bring in much needed convergence of resources with different Ministries and Departments could provide fillip to the programme.

We need to strengthen micro-credit system for establishing micro-enterprises in the watershed areas. The bigger financial institutions would seldom come to the help of small enterprises with little capacity to pay back the loans at higher interest rates. The micro finance institutions, to the contrary, would extend small loans at low interest rates and flexible time limits. The setting up of more *Gramin* Banks and Cooperative Societies in the rural sector is desired besides strengthening National Bank for Agriculture and Rural Development (NABARD).

Reclamation of salt affected soils

About 8.5 million ha of cultivated soils affected by alkalinity and salinity have very low productivity due to unfavourable conditions for growing of crops in India (Anonymous 2004b). The states most affected are Uttar Pradesh, Gujarat, Rajasthan, West Bengal and Andhra Pradesh. The high pH, exchangeable sodium and salt contents inhibit transformation and availability of native and applied nutrients. The soils are, generally, deficient in Ca, N and Zn. The deficiency of Mn has recently been reported in wheat grown on calcareous and light textured alkali soils. The technology has been developed to reclaim these soils through addition of amendments, drainage, growing of salt tolerant varieties, bio-drainage and proper use of poor quality waters. Over 1 million ha of barren alkali lands have been reclaimed, realizing productivity of about 8 t ha^{-1}. The potential exists for increasing food production by another10-15 million tonnes per annum by reclaiming more areas under sodic lands.

Besides amelioration of existing salt affected lands, conscious efforts need to be made in preventing secondary salinization of lands. The excess use of canal water has led to salinization in major irrigation commands of the country.

Amelioration of acid soils

The productivity of acidic soils, particularly with pH < 5.5, is low due to deficiencies as well as toxicities of some nutrients. The soils need liming to neutralize active and part of exchange acidity and application of fertilizers to ensure adequate supplies of nutrients to crops. The earlier approach of liming of soils based on lime requirement (2-4 t ha^{-1}) and broadcast method of application proves uneconomical. The application of lime @ 1/10th of lime requirement in furrows along with the fertilizers is cost-effective and acceptable to the farmers. The conjunctive use of lime and fertilizers on 871 farmers' fields under ICAR Network Project on Acid Soils has increased yields of a variety of crops by 49-189 % over farmer's practice (Sharma and Sarkar 2005). Liming could save half of the recommended fertilizer, especially for legumes and pulses (Table 6). The adoption of technology on 10 million ha of these lands would contribute at least 10 million tonnes of additional food grains to the national food basket per annum.

The cost-effective technology requires to be operationalized by creating requisite infrastructure for marketing and distribution of liming materials and creating more awareness on usefulness of the technology among farmers. The cheap and effective liming materials like basic slag and lime sludges are available with steel industries and paper mills, respectively.

Table 6 Effect of liming on crop yield (q ha^{-1}) in acid soils

State	Crop	100% NPK	50% NPK +Lime
Assam	Rapeseed	9.70	10.10
	Summer green gram	4.42	5.17
Kerala	Cowpea	8.57	10.65
	Black gram	6.38	8.10
Meghalaya	Maize	30.50	30.30
	Groundnut	14.20	21.30
West Bengal	Mustard	8.15	8.40
	Wheat	16.70	17.15
Jharkhand	Maize + Pigeon pea (Maize equiv. yield)	69.0	65.0
	Pea	38.4	50.8
Orissa	Groundnut + Pigeon pea	22.5+12.0	23.6 + 12.2
HP	Maize	34.0	33.1
	Wheat	27.9	23.7

Source: Sharma and Sarkar 2005

Mitigating climate change

The climatic change due to increased green house gases emissions and global warming is going to have far reaching repercussions on the sustainability of agriculture and food security in the near future. The change is likely to alter agro-meteorological parameters, overall crop-water balance, pest and disease incidence and land use etc. It has been estimated that an increase of 0.5^{0}C in mean temperature in Punjab, Haryana and Uttar Pradesh would have reduced the productivity of wheat crop by 10%. The melting and receding of Himalayan glaciers (Table 7), regulating water and hydro-power supplies to adjoining Indo-Gangetic plain, puts a big question mark on the sustainability of agriculture in the northern states of the country.

There is already 16 % loss in glacial area over the past 40 years. The Inter Governmental Panel on Climate Change in its Fourth Assessment Report (IPCC, 2007) has projected warming of 0.2^{0}C per decade in the next two decades, even if the concentration of all green house gases and aerosols remains constant at year 2000 level. As glaciers melt, sea levels would also rise and inundate low-lying resource rich coastal regions and islands. The global warming is also projected to increase water, shelter and energy requirement of livestock and affect fish breeding, migration and harvests. The rising temperatures may affect productivity of temperate fruits like apple. The decline in apple productivity in Simla and Kullu districts of Himachal Pradesh in recent years is linked to inadequate chilling to crop due to prevalent warm weather (Bhagat et al. 2007). There is a shift in the apple belt towards higher reaches in Lahaul & Spiti and Kinnaur districts of Himachal Pradesh.

Table 7 Basin wise loss in glacial area

Basin	No. of glaciers	Area 1962 (Km^2)	Area 2001/2004 (Km^2)	Loss in Area %
Chandra	116	696	554	20
Bhaga	111	363	254	30
Parbati	90	493	390	20
Basapa	19	173	140	19
Warwan	253	847	672	21
Bhut	189	469	420	10
Miyar	166	568	523	08
Alaknanda	126	734	638	13
Bhagirathi	187	1218	1074	11
Gauriganga	60	305	256	16
Total	1317	5866	4921	16

Source: Kulkarni et al. 2009

Naturally, we can afford to release only a limited amount of carbon into the atmosphere to keep the greenhouse warming effect within safer limits. A temperature increase of 1°C is the maximum that could be allowed. This safe limit is bound to be reached in just 40 years if we continued with the present state of affairs.

Developing new genotypes suitable to the changing climatic situations should be a major priority. The research efforts need to be intensified employing marker assisted selections and transgenic approaches to evolve cultivars tolerant to droughts, high temperatures, water logging and new emerging pests and diseases. The C3 plants could be transformed into C4 plants to lower the elevated carbon dioxide levels in the atmosphere, while at the same time enhancing photosynthetic activity and crop productivity. The new land use and management systems requiring least soil disturbances and minimal soil carbon loss into the atmosphere need to be devised for different regions. The conservation tillage and aerobic –rice systems deserve a special mention in this regard. The pests and disease forecasting systems covering range of climatic parameters need to be developed for contingency planning and effective pest/disease management. The knowledge based decision support systems for translating short, medium and long range weather forecasts into operational management practices should be strengthened for reducing production risks. The simple manipulations in terms of planting dates (extending or delaying) to escape aberrant weather changes due to climate need to be identified. The soil, water and fertilizer management practices that reduce GHG emissions of methane and nitrous oxide (Aulakh and Adhya 2006) merit their adoption.

Although India's share in total emissions is relatively less, it should participate vigorously being a responsible member of international community in collective global efforts in reducing emissions. The large area under waste lands in our country could be gainfully employed for sequestration of green house gases by taking up large scale plantations. The potential for sequestration of organic carbon through restoration of degraded and desertified soils in India is 10 –14 Tg C yr^{-1} (Lal 2004). The Indian farmers would be benefitted greatly by carbon trading projects both from sale of timber and carbon credits. There is growing interest in the country to bring about 2.5 million ha of wastelands under bio-fuel plantations of Jatropha (Jatropha curcas) and Karanja (Pongamia pinnata) to supply 2.6 million tonnes of biodiesel in order to blend 5% petrodiesel with biodiesel. Besides carbon sequestration, we need to develop speedily non-carbon sources of energy like hydro-power, nuclear, solar and wind energies and enhance energy use efficiencies in industry, transport, domestic appliances and agriculture.

Epilogue

Providing food and nutritional security to growing population has been central to

development planning in India. The country would require about 280 million tonnes of food grain by 2020, with annual growth rate of 2 percent. With cultivated area remaining static, the desired growth in production has to come with the increase in productivity. The growth rates of Total Factor Productivity are, however, decelerating for quite sometime, endangering food security. The factors impacting factor productivity have to be identified and addressed to have the growth of agriculture on a higher trajectory. The declining response of fertilizers, contributing over 50 percent towards productivity, for the last 30 years or so is a matter of great concern. The imbalanced fertilizer use in terms of NPK and micro and secondary nutrients coupled with less use of organic manures has given rise to this situation. The solution lies in the widespread adoption of integrated nutrient management, envisaging conjunctive use of inorganic and organic fertilizers. We need to augment the supplies of organic manures, composts/vermicomposts and biofertilizers, which are still in short supply. To have adequate and sustained supplies of fertilizers, the fertilizer industry facing stagnation for almost a decade requires to be bailed out through appropriate policy initiatives. It is high time, the fertilizer industry looked forward towards production of soil and crop specific fortified, coated and customized fertilizers. The completely water soluble fertilizers, ideal for fertigation systems, need to be produced in the country to make them cost-effective.

The share of irrigation water is going to drop from 83 percent to 72 percent in the near future, given the growing competition for fresh water from domestic and industrial sectors. The problem is likely to be compounded with slow execution of multi-purpose projects, drying up of ground water resource, complexities in negotiations on inter-basin river water transfers and crop-water imbalances under impending climate change. The focus, therefore, requires to be given on improved water management at basin, command and farm levels. The rainfed areas occupying 87 million ha and supporting 40 percent of food, determine food security to a large extent. These areas require special attention to bridge the gaps in production technologies and allocation of resources. The establishment of National Rainfed Authority is a right step in this direction. The amelioration of 3 million ha of salt affected and 10 million ha of acidic lands could add about 25 million tonnes of additional grain to the national food basket.

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Global impacts of human mineral malnutrition

Alexander J Stein

Abstract Malnutrition - in the form of insufficient energy intakes - affects millions of people worldwide and the negative impact of this kind of hunger is well acknowledged, not least by agronomists trying to increase yields to ensure a sufficient supply of food. Scope: This review focuses on another, more particular and "hidden" form of malnutrition, namely mineral malnutrition. It illustrates the burden of disease that is caused by mineral deficiencies and the social and economic consequences they bring about. Conclusions: Mineral malnutrition has a considerable negative impact on individual well-being, social welfare and economic productivity. Agricultural scientists should keep the nutritional qualities of food in mind and - next to optimizing the agricultural properties of crops that are paramount for their adoption by farmers - in particular try to increase the micronutrient content in major staple crops as one way to address vitamin and mineral malnutrition in humans; especially plant breeding approaches promise to be very cost-effective.

Keywords Human • micronutrient malnutrition • mineral deficiencies • burden of disease • social and economic costs • biofortification

Abbreviations CaD: Calcium deficiency, CGIAR: Consultative Group on International Agricultural Research, FAO: Food and Agriculture Organization of the United Nations, FeD: iron deficiency, FeDA: iron deficiency anemia, GDP: gross domestic product, GM: genetically modified, ID: iodine deficiency, IPR: intellectual property rights; SeD: selenium deficiency, VAD: vitamin A deficiency, VMD: vitamin and mineral deficiency, WFP: World Food Programme, WHO: World Health Organization, ZnD: zinc deficiency

Introduction

In humans, malnutrition is mostly understood to mean chronic hunger. According to estimates of the Food and Agriculture Organization of the United Nations (FAO

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2009), currently over one billion people worldwide – one out of six – are thus undernourished. The related negative global impacts of undernutrition on individual well-being and economic growth are well acknowledged and there is general agreement that fighting hunger not only represents one of the foremost challenges for humanity but also offers considerable economic and social returns (FAO 2008a; Horton et al. 2008; WFP 2007; World Bank 2006; Sanchez et al. 2005; Fogel 2004). In any case, going beyond ethical and economic considerations, the Economic and Social Council of the United Nations affirmed the legal obligation by every state "to ensure for everyone under its jurisdiction access to the minimum essential food which is sufficient, nutritionally adequate and safe, to ensure their freedom from hunger" (UN 1999).

Yet, apart from this outright hunger – the reasons and consequences of which are obvious to both the individuals concerned and to their social environment – over the last two decades the definition of malnutrition increasingly also covers so-called "hidden hunger" (Allen 2003a; WHO 2004).[1] This form of hunger is caused by a chronic lack of vitamins and minerals that is called "hidden" because people who suffer from it do not feel they lack something and its consequences are often not immediately visible (MI 2009); hence entire populations can be affected by this kind of malnutrition, even if the food supply is adequate in preventing "classical" hunger (Kennedy et al. 2003a). The global impacts of human malnutrition with minerals are the subject of the present review.

Impacts of human mineral malnutrition

There are at least twenty dietary minerals and trace elements that are – or are plausibly suspected to be – essential for the proper functioning of the human body (Table 1; for a recent review of the role of minerals in plants and human health also see Martínez-Ballesta et al. 2009). Consequently, if they are not ingested in adequate amounts (or are poorly bioavailable), there will be negative impacts on the health of those who consume too little of these nutrients. Still, many minerals are needed in such small amounts or are so abundantly available in many foodstuffs that the occurrence of related deficiencies is rare or even unknown. On a global level, and in particular in developing countries, it is above all deficiencies in iron (*Fe*), zinc (*Zn*) and iodine (*I*) that are recognized to have a negative impact on public health (Horton et al. 2008; Ezzati et al. 2004; WHO 2002).[2] Also deficiencies in calcium (*Ca*) and selenium (*Se*) are considered to represent public health problems, albeit less significant ones (Black et al. 2008; Allen et al. 2006; WHO 2004; Pettifor 2004), and in sub-populations or at regional levels also deficiencies in magnesium (*Mg*) and copper (*Cu*) may represent more common health problems (White and Broadley 2009; JN 2009; Biesalski et al. 2003; Black 2001; Bhan et al. 2001).[3] As the focus of this review is on the *global* impact of human malnutrition with minerals, in the following only the impacts of iron deficiency (FeD), zinc deficiency (ZnD) and iodine deficiency (ID) will be discussed in greater detail, but where appropriate and available also information on calcium deficiency (CaD) and selenium deficiency (SeD) will be included.

Regarding the prevalence of the main mineral deficiencies, the prevalence of (more severe) FeD is generally approximated by the prevalence of anemia because it is its primary cause, even if not all FeD manifests in anemia and not all anemias are due to FeD. (In general 50-60% of anemia can be attributed to FeD, although this share may be lower in regions where e.g. hookworms or AIDS are prevalent (Stein et al. 2005)). De Benoist et al. (2008) estimate that 25% of the global population (1.6 billion people) suffers from anemia, and the World Health Organization (WHO 2009a) puts the number of anemic people at 2 billion people (over 30% of the world's population). The WHO also confirms that FeD is the most common and widespread nutritional disorder in the world, predominantly affecting children and women in both developing *and* industrialized countries. A similar share of the world population may be affected by ZnD; the WHO (2002) estimates that 2 billion people (33%) are not consuming the "US recommended dietary intake" of *Zn* and Hotz and Brown (2004) estimate that 1.2 billion (20%) are at risk of inadequate *Zn* intakes. For ID de Benoist et al. (2004) estimate that 35% of the general population (2 billion individuals) have insufficient *I* intakes. While underlining the difficulty to quantify the total number of people suffering from SeD worldwide, Combs (2001) puts forward an estimate of 0.5-1 billion (i.e. roughly 10-15%). Similarly, Allen et al. (2006) do not find sufficient data to quantify a global prevalence of SeD nor of CaD, but for *Se* they report severe deficiency in some regions of various countries and for *Ca* they confirm that low intakes are very common. For nutritional rickets in general, which can be a consequence of CaD or vitamin D deficiency, Bereket (2003) states that it remains

[1] The FAO and the WFP differentiate between "malnutrition" (the physical condition resulting from inadequate or unbalanced nutrient intakes or their poor absorption), "undernutrition" (the physical manifestation of prolonged low level food intakes with serious deficiencies in one or a number of macronutrients and micronutrients), "undernourishment" (a situation where people's food intakes are continuously insufficient to meet their basic *energy* requirements), "micronutrient deficiency" (lack of essential *vitamins and minerals* as a result of malnutrition) and, less of relevance in the present context, "overnutrition" (the physical condition resulting from an excess of certain nutrients, which also falls under "malnutrition") (FAO 1999; WFP 2007). Yet, as the WFP acknowledges, there is some disagreement on what these terms mean and how they relate to each other. Nevertheless, despite being somewhat artificial, such a categorization may offer a relatively clear and consistent way of approaching the issues.

[2] In this context usually also vitamin A deficiency (VAD) is listed, but as the focus of this article is on minerals, vitamin malnutrition is not further considered here.

[3] Even though potassium is an essential mineral (for which e.g. in the USA health claims on foods are permitted), potassium deficiency due to insufficient potassium in the diet is rare and not commonly considered a public health problem; deficiency is rather caused by excessive losses or poor retention.

Table 1 Function of minerals and elements in humans (IOM 2001, IOM 2004, JN 2009)

	IOM (2001)	JN (2009)
Arsenic (*As*)	No biological function, although animal data indicate a requirement.	Has been shown to have beneficial actions when fed in very small amounts to laboratory animals, but its physiological role has not been clearly defined.
Boron (*B*)	No clear biological function, although animal data indicate a functional role.	May be essential for humans based on recent experimental evidence showing that boron affects blood biochemical markers of energy and mineral metabolism.
Calcium (*Ca*)	Essential role in blood clotting, muscle contraction, nerve transmission, and bone and tooth formation.	Structural function (stores in the skeleton), electrophysiological function (carries charge during an action potential across membranes), intracellular regulator, and cofactor for extracellular enzymes and regulatory proteins.
Chloride (*Cl*)	As sodium chloride (salt) required to maintain extracellular volume and plamsa osmolality (IOM 2004: 269).	As sodium chloride (table salt) required for maintenance of extracellular fluid volume.
Chromium (*Cr*)	Helps to maintain normal blood glucose levels.	Required for normal sugar and fat metabolism, potentiates the action of insulin.
Copper (*Cu*)	Component of enzymes in iron metabolism.	Part of enzymes that help biochemical reactions in every cell, involved in the absorption, storage and metabolism of iron.
Fluorine (*F*)	As fluoride inhibits the initiation and progression of dental caries and stimulates new bone formation.	As fluoride serves as catalyst for the mineralization of developing tooth enamel and for remineralization of surface enamel; reduces occurrence of dental decay (caries).
Iodine (*I*)	Component of the thyroid hormones; and prevents goiter and cretinism.	Essential component of thyroid hormones, which regulate cell activity and growth in virtually all tissues and are essential for normal embryonic and postnatal development.
Iron (*Fe*)	Component of hemoglobin and numerous enzymes; prevents anemia.	Carries oxygen and forms part of hemoglobin in blood and myoglobin in muscles; component of various enzymes.
Magnesium (*Mg*)	Cofactor for enzyme systems.	Important role in 300+ fundamental enzymatic reactions, in the activation of amino acids, the synthesis and degradation of DNA, in neurotransmission and immune function.
Manganese (*Mn*)	Involved in the formation of bone and in enzymes in the metabolism of amino acid, cholesterol and carbohydrate.	Part of several enzymes (preventing tissue damage, breaking down carbohydrates, nitric oxide synthesis, urea formation); activates numerous enzymes (cartilage formation).
Molybdenum (*Mo*)	Cofactor for enzymes involved in catabolism of sulfur amino acids, purines and pyridines.	Component of a number of enzymes (metabolism of sulfur amino acids, oxidation of purines and pyrimidines, production of uric acid, oxidation of aldehydes).
Nickel (*Ni*)	No clear biological function identified; may serve as a cofactor of metalloenzymes and facilitate iron absorption or metabolism in microor-ganisms.	Cellular effects documented but no deficiency disease in man; found in highest concentrations in lung, kidney and some hormone-producing tissues; can activate or inhibit a number of enzymes that usually contain other elements.
Phosphorus (*P*)	Maintenance of pH, storage and transfer of energy and nucleotide synthesis.	The metabolism of all major metabolic substrates depends on its functioning as a cofactor in a variety of enzymes and as the principal reservoir for metabolic energy.
Potassium (*K*)	Required for cellular function; deficiency can cause cardiac arrhythmias, muscle weakness, glucose intolerance, high blood pressure, salt sensitivity, risk of kidney stones, high bone turnover and risk of cardiovascular diseases (IOM 2004: 186).	The most essential cation of the cells; because of its association with the metabolizing, oxygen-consuming portion of the body, a decline in total body potassium is usually interpreted as a loss of muscle mass due to a catabolic condition.
Selenium (*Se*)	Defense against oxidative stress and regulation of thyroid hormone action.	Functions as a component of enzymes involved in antioxidant protection and thyroid hormone metabolism.
Silicon (*Si*)	No biological function identified; in animal studies involved in bone function.	May play a role in structure of glycosamino-glycans and their protein complexes; no human data available.
Sodium (*Na*)	As sodium chloride (salt) required to maintain extracellular volume and plamsa osmolality (IOM 2004: 269).	Predominant cation in extracellular fluid; acts in consort with K, the chief cation of intracellular fluid, to regulate body water distribution and blood pressure; important for acid-base balance and the transmission of nerve impulses.
Sulfur (*S*)	As inorganic sulfate required for the synthesis of PAPS, which is required for synthesis of many important sulfur-containing compounds (IOM 2005: 424).	n/a
Vanadium (*V*)	No biological function identified.	No specific biochemical function has been identified.
Zinc (*Zn*)	Component of multiple enzymes and proteins; involved in the regulation of gene expression.	Structural, catalytic and regulatory roles; role in the coding for zinc finger proteins; required by over 60 enzymes for activity, incl. RNA polymerases; supports synaptic vesicles.

prevalent in developing countries all around the world, even if its prevalence is highly variable between countries and regions. The difficulty of substantiating the reach of mineral deficiencies is also highlighted by Borwankar et al. (2007) who find in their analysis of the magnitude of vitamin and mineral deficiencies (VMDs) that – for other minerals but *I* and *Fe* – "we do not have data on the prevalence of other micronutrient deficiencies. Surveys are needed to fill these gaps. We need to develop, field test, and apply field methods for other micronutrients."

Health consequences of human mineral malnutrition

Inadequate intake of bioavailable dietary *Fe* leads to FeD, severe FeD results in iron deficiency anemia (FeDA), and anemia is subdivided into mild, moderate and severe anemia. While further adverse health outcomes are suspected to be attributable to FeDA, it is generally accepted that at least the following three are caused by FeDA: impaired physical activity, impaired mental development in children, and maternal mortality (which indirectly leads to further negative outcomes such as stillbirths and child deaths due to lack of breastfeeding and care) (Stein et al. 2005). In the case of ZnD the related adverse health outcomes are only documented for infants and children; these outcomes are stunting, diarrhea and pneumonia, with the latter two also contributing to overall under-five mortality (Stein et al. 2005). For ID the health consequences are goiter, irreversible mental retardation and, at the more extreme end, cretinism (which in severely endemic areas may reduce the mean IQ in the population by over 10 points) (de Benoist et al. 2004).[4] CaD is the major cause of rickets in Africa and parts of tropical Asia, but in other parts of the world – including an industrialized country like the USA – rickets is also recognized as an adverse health outcome of CaD in infants and children (Thacher et al. 2006; DeLucia et al. 2003). Calcium is also important for bone and bone tissue health in adults and insufficient supplies can lead to osteomalacia and osteoporosis (Nieves 2005; Allgrove 2004; Heaney 2003). Research findings also indicate that CaD may negatively influence a variety of chronic diseases, including type 2 diabetes (Nicklas 2003; Pittas et al. 2007). Overt SeD is primarily associated with Keshan disease, a cardiomyopathy that is frequently fatal and affects mainly children and women of childbearing age; marginal SeD may increase the mortality and cancer risk, contribute to cognitive decline and coronary heart disease, and impact on male and female reproduction (Rayman 2008; Broadley et al. 2006). For all minerals there is also the possibility of excessive intakes that may have adverse health effects and toxicity can become

[4] Stunting can also be an outcome of undernourishment; in cases where undernourishment and ZnD occur in parallel, ZnD increases the prevalence or severity of stunting (Stein et al. 2005).

an issue. However, excessive intakes are generally less widespread and are not of concern in this context.

Burden of disease of human mineral malnutrition

The previous section highlighted the health consequences that can occur with the most common forms of human mineral malnutrition, ranging from bouts of diarrhea to premature death. While the magnitude of some of the health consequences is more intuitive, the dimensions of others are more difficult to grasp. Hence, given the different health outcomes of the various mineral deficiencies, their overall health loss cannot simply be aggregated for individual deficiencies nor can their severity be compared across different deficiencies. To quantify and compare the burden of disease of each deficiency means that the health losses due to each adverse health outcome need to be quantified and expressed in common units of measurement. Addressing the issue of how to measure "health", the World Bank (1993) introduced "disability-adjusted life years", or DALYs, a concept that was further popularized through the WHO's "Global Burden of Disease" project (WHO 2009b) and the seminal book by Murray and Lopez (1996); for FeD and ZnD the DALYs method has been refined by Stein et al. (2005; 2009).

In essence, DALYs combine the health loss due to cause-specific morbidity and mortality in a single index, with one DALY being equal to the loss of one "healthy" life year. In the case of mortality the loss corresponds to the remaining standard life expectancy at the age of death, expressed in years; for morbidity the health loss is calculated from the average duration of the disease (also expressed in years), which is multiplied by a weighting coefficient to capture the severity of the disease and the loss of quality of life. (This coefficient can range from 0, i.e. no health is lost, to 1, i.e. all health is lost.) With this, the "burden" of a health outcome is calculated across all affected individuals by summing up the "years of life lost" (YLL) due to cause-specific mortality and the "years lived with disability" (YLD). More formally this can be represented as:

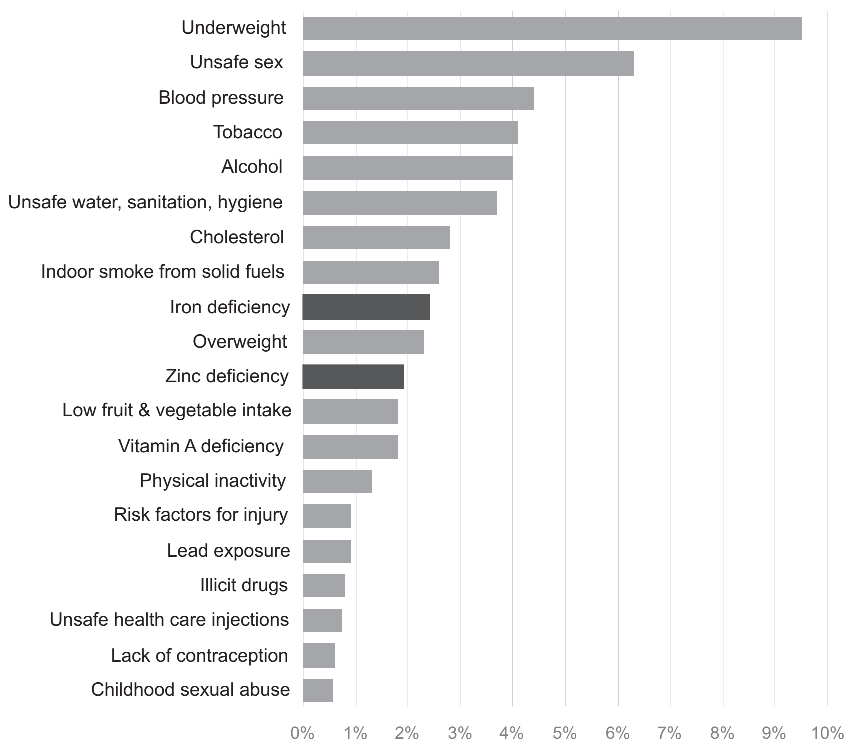
$$\mathrm{DALYs}_{\mathrm{lost}} = \mathrm{YLL} + \mathrm{YLD}_{\mathrm{weighted}}$$

Once the DALYs lost due to each adverse health outcome of a deficiency are determined they can be aggregated to yield the overall burden of the corresponding deficiency. Using this method in a comprehensive study, the WHO (2002) described the amount of disease, disability and death in the world due to the most important health risks; in this context also the global burdens of FeD, ZnD and ID were calculated. As can we seen in Table 2, these three most important forms of mineral malnutrition are estimated to have caused the loss of over 65 million DALYs worldwide in the year 2000 – representing almost 5% of the overall burden of disease caused by the major health risks. Furthermore, in the

Table 2 Global burden of selected nutritional risks in 2000 (WHO 2002)

	Million DALYs lost	Share in overall burden
Most important risks to human health	1,455.0	
Considered nutritional risks (underweight, VAD, FeD, ZnD, ID)	230.0	15.8%
Considered VMDs (VAD, FeD, ZnD, ID)	92.2	6.3%
Considered mineral deficiencies (FeD, ZnD, ID)	65.6	4.5%
Iron deficiency (FeD)	35.1	2.4%
Zinc deficiency (ZnD)	28.0	1.9%
Iodine deficiency (ID)	2.5	0.2%

Fig. 1 The 20 leading health risks and their share in the overall burden of disease (WHO 2002)

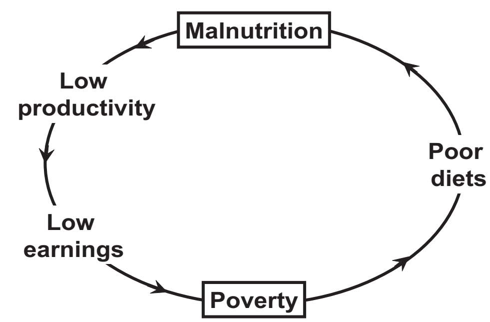


ranking of the burdens of disease caused by each health risk, FeD represents the 9th and ZnD the 11th biggest health risk worldwide (Fig.1). In this study only FeD, ZnD and ID were considered; no comparable analysis is available for other mineral deficiencies. Given that ID, the third mineral deficiency considered by the WHO, represents a relatively smaller health risk than either FeD or ZnD, it can be assumed that – at the global level – the other mineral deficiencies, in particular CaD and SeD, also represent relatively smaller public health problems.

Socio-economic impact of human mineral malnutrition

So far it has been shown that mineral deficiencies affect billions of people, causing disease and suffering at the level of the individual, and contributing considerably to the burden of disease that is borne by the societies they are living in. However, next to this social cost, mineral malnutrition also imposes tangible economic costs by hampering both individual productivity and overall economic growth, i.e. apart from the human and moral necessity to help those suffering from hunger, malnutrition and ill health, there is also a purely economic rationale for controlling malnutrition. This rationale is based on the notion that it is not the poor who are hungry but the hungry who are poor – or rather, that there is a vicious circle of mutually reinforcing hunger and poverty (Fig. 2).

Fig. 2 The malnutrition-poverty trap (Stein 2006)



The idea that the income of individuals depends on their productivity and that their productivity depends on the nutritive value of their food intakes – and not only the other way round – goes at least back to Leibenstein (1957). He also already pointed to "evidence relating not only calorie intake, but also other nutritive elements to output, either directly or indirectly through their effect on such things as debilitating disease, absenteeism, and lethargy" (Leibenstein 1957: 96, emphasis added) and he linked individual undernutrition and national underdevelopment. However, Leibenstein and other early researchers did not analyze low productivity from a nutrition or health point of view; the interest was rather to explain the functioning of the rural wage and labor system. In this context poor nutrition was merely seen as a consequence of surplus labor in rural areas: because of too little available work, workers earn very little, but for the same reason there is no need for them to be more productive (see Stein 2006).

In subsequent work the interaction between nutrition and work capacity was analyzed more in view of increasing agricultural productivity. While for instance Ward and Sanders (1980) have reported that higher incomes can lead to improved food intakes, others (Strauss 1986; Deolalikar 1988; Haddad and Bouis 1991; Alderman et al. 1996) have provided empirical support showing that the mechanism can also work the other way round, i.e. that better nutrition can increase individual productivity – or that chronic malnutrition can impact negatively on market wages and farm output. In a review of the literature on the nutrition-productivity link, Strauss and Thomas (1998) have also concluded that there is not only a strong effect of income on health, but that – at least in low-income settings – there exists a causal impact of health on wages and productivity. While these studies addressed the malnutrition-productivity link more from an economic point of view and with a focus on insufficient energy intakes, there is also a wealth of medical and nutrition literature confirming the negative impact of FeD on productivity (for an overview see e.g. Haas and Brownlie 2001). In an economic analysis Weinberger (2003) estimated that *Fe* sufficiency could increase the wages of agricultural laborers in India on average by 5-17%. And only recently Jha (2009) re-confirmed the existence of malnutrition-poverty traps, also for India, explicitly including the impact of VMDs.

Apart from a direct impact on individual productivity and personal earnings, in the aggregate malnutrition also affects overall economic growth and national income. This, in turn, keeps labor demand down, suppresses wages and, thus, aggravates malnutrition: another vicious circle. Low national incomes also limit public resources that can be used for nutrition and health interventions – when health care costs (both at the individual level and in the public health system) are already increased through malnutrition. Finally malnutrition also affects future productivity and income, e.g. when malnourished mothers have smaller babies that are more prone to suffer from diseases later on in life, or when malnutrition in children – in particular with *I* and *Fe* – leads to reduced cognitive abilities and to deficits in schooling (Horton et al. 2008; World Bank 2006; FAO 2004; Behrman et al. 2004; Broca and Stamoulis 2003; WHO 2001). Given this body of evidence, it is not surprising that in last year's food crisis the need to break the malnutrition-poverty trap has been highlighted by the FAO (2008b) as well.

Estimating the impact of malnutrition on overall economic growth, Arcand (2001) found that an inadequate dietary energy supply is responsible for a shortfall of 0.2-4.7% in the annual growth rate of global per capita income. Extending this analysis, Wang and Taniguchi (2003) confirmed that better dietary energy supply

is associated with faster economic growth. However, for developing countries with severe food shortages they also found a population effect, i.e. for improved nutrition to contribute to (per capita) economic growth, population growth needs to be controlled. In a historic analysis, Fogel (2004) found that 30% of the growth in British per capita income over the last two centuries was due to better overall nutrition (including vitamins and minerals). Focusing more specifically on vitamins and minerals, the World Bank (1994: 2) suggested already 15 years ago that "deficiencies of just vitamin A, iodine, and iron could waste as much as 5% of gross domestic product, but addressing them comprehensively and sustainably would cost less than 0.3% of gross domestic product (GDP)." In a more detailed analysis of the economic impact of FeD through mental impairment and low work productivity, Horton and Ross (2003) calculated for a sample of ten developing countries a median loss of GDP of 4%. For "all forms" of VMD (FeD, ID, VAD and folate deficiency are specifically mentioned), the Micronutrient Initiative and UNICEF put forward losses of over 2% of GDP for individual countries (Adamson 2004). These estimates confirm that malnutrition in general and VMDs in particular have a significant negative impact on economic growth. And even if only the lower-bound estimates are true, as the current economic crisis shows, 1-2% difference in economic growth have substantial implications for national economies and social welfare (e.g. G-20 2009). Moreover, the dynamic aspect of successive increases in national income becomes evident from the analysis by Fogel (2004): better nutrition and somewhat higher economic growth today and tomorrow means a much higher income for future generations.

However, economic growth and a higher GDP are no ends in themselves; they are means to support human development (longevity, knowledge, decent standards of living, participation) and happiness (UNDP 2009; Thinley 1998) – dimensions that are also reflected in the United Nations "Millennium Development Goals", which cover the reduction of poverty and hunger, the achievement of universal primary education and gender equality, the reduction of child mortality and maternal mortality, the reversal of the spread of major diseases, the guarantee of environmental sustainability, and the creation of a global partnership for development (UN 2000). In as far as mineral malnutrition increases mortality, morbidity and susceptibility to infectious diseases, reduces cognitive abilities, physical performance and earning potential, and disproportionately affects children and (young and pregnant) women, as has been shown in the previous sections, it also has a decidedly negative impact on most of these indicators.

Causes and determinants of malnutrition

Hunger in general – as a result of food insecurity – has four main causes: (i) *unavailability* of food, (ii) lack of *access* to food and (iii) its poor *utilization* (due to a person's inability to select, take-in and absorb the nutrients in the food). Moreover, these causes can be affected by the (iv) *vulnerability* of an individual (i.e. by physical, environmental, economic, social and health risks) (WFP 2007). In particular in the case of VMDs, another cause can be the *loss* of nutrients (e.g. Ramakrishnan and Yip 2002). Finally, changes (reductions) in the micronutrient *content* of common crops can also contribute to VMDs.

Unavailability of food at the regional level can be a consequence of disasters – whether man-made or natural – that disrupt the food supply or the access to it; similarly seasonal variations in local food availability and food shortages may contribute to VMDs (FAO 2008; WFP 2007; Allen et al 2006; WHO 2004).

Regarding the access to food, this is part of the other half of the vicious circle described in the previous section: poverty can be a major underlying cause of malnutrition by limiting people's access to food (Horton 2009; FAO 2008a; Black 2008; Allen et al. 2006; Strauss and Thomas 1998). At the household level the distribution of food within the household can also be a factor limiting individuals' access to (micronutrient-rich) food. However, at least for India no general, nationwide and persistent biases in the intra-household distribution of food could be found (see Mahendra Dev 2003; Stein et al. 2007; 2008a). Other household characteristics are more relevant in determining the access to food: smaller households as well as households that engage in agricultural activities seem to be better able to secure higher food consumption and better micronutrient intakes for their members (Ward and Sanders 1980; Wolfe and Behrman 1983; Chernichovsky and Meesook 1984; Block 2002; Stein 2006; Liu and Shankar 2006). At the national level low incomes contribute to malnutrition by setting a ceiling for public and private investments that could otherwise address underlying determinants of (child) malnutrition, like care for mothers and children or the quality of the health environment (Smith and Haddad 2000). However, e.g. Haddad et al. (2003) found that income growth alone may not be sufficient to markedly reduce hunger in the foreseeable future, and also the WFP (2007) states that income growth alone does not lead to sufficient improvements in nutrition and health, especially if economic progress does not "trickle down" to the poor.

In the case of VMDs poverty also influences people's nutrition in a different way: poverty – just like the recent food price shocks – forces people to reduce not only the number of their meals, which reduces their absolute nutrient intakes, but also the diversity of their diets and hence their food security (FAO 2009; Ruel 2003). When diverse diets are or become unaffordable, switching to relatively cheaper staple foods can help the poor maintain their energy intakes, thus preventing outright hunger. Yet, more monotonous diets that are poor in fruit, vegetables and animal source foods result in low micronutrient intake and poor bioavailability, especially of minerals (FAO 2008a; WFP 2007; Allen et al. 2006). Hence monotonous diets can also be responsible for poor utilization of the (little) food that is accessible to the poor.

In the context of VMDs, poor utilization of food that is both available and (theoretically) accessible can also result from food preferences in which micronutrients are not directly included, i.e. households do not demand micronutrients per se but select their food according to many other, more highly valued food attributes (Behrman 1995). Correspondingly, Ward and Sanders (1980) found for urban migrants in Brazil that they were not able to utilize increased income to qualitatively improve their diets. Pitt (1983) found for rural Bangladesh that poor households could improve their nutrition by altering their food preference patterns, i.e. with better nutrition knowledge they could achieve better nutrition outcomes for their given (low) level of income. Behrman and Deolalikar (1987) found for rural south India that income increases are not primarily used to obtain more nutrients. And Bouis and Novenario-Reese (1997) found that food preferences have a negative impact on nutrient intakes and that consumers could satisfy them relatively inexpensively if they were aware of their micronutrient needs. A related issue is the "nutrition transition" occurring in many parts of the developing world, which is only partially explained by economic factors alone and which can lead to the coexistence of both overnutrition and micronutrient malnutrition in the same population (Popkin 2001; Popkin et al. 2001; FAO 2006).[5] However, in cases where highly-valued food (which people can afford with rising incomes) incidentally also contains higher levels of micronutrients, fighting poverty can automatically help reducing VMDs. For instance in one recent study Kwun et al. (2009) found that *Zn* nutrition in South Korea improved markedly in the period of rapid economic growth between 1969 and 1998: lower *Zn* intakes due to decreased cereal consumption were counterbalanced by marked increases in the consumption of meat and fish as well as by improved *Zn* bioavailability due to reduced phytate consumption.

Food choices that disregard micronutrients can also result from poor nutrition knowledge and low education in general (Horton 2009; FAO 2008a; WFP 2007; Allen et al. 2006). Consequently, both general schooling and nutrition education – especially of women and of those with poor educational backgrounds – have been shown to improve micronutrient status and the overall adequacy of the diets consumed in the respective households (Chernichovsky and Meesook 1984; Smith and Haddad 2000; Block 2002; Webb and Block 2003; Abdulai and Aubert 2004; Kandpal and McNamara 2009). Improving women's status more generally can also contribute to increased female nutrient status through delayed childbearing and fewer pregnancies (Ramakrishnan and Yip 2002). Poor maternal nutrition – with ensuing fetal undernutrition – is particularly damaging because the adverse health effects of a basic lack of protein and energy can be compounded by VMDs and have negative impacts on the thus born children's growth, their

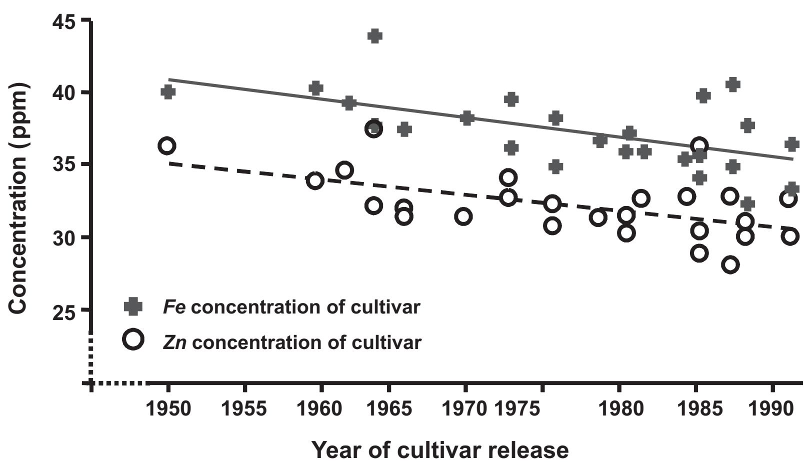
[5] Other authors suggest that causal relationships may exist between micronutrient deficiencies and obesity in different populations (García et al. 2009).

development and the nutritional status for the rest of their lives (WHO 2002; Black et al. 2008; Bhutta and Haider 2009; Dickinson et al. 2009).

Regarding the loss of nutrients as one cause of malnutrition and VMDs, this can result from disease – which itself is linked to poverty. Similar to the interaction between hunger and poverty, malnutrition does not only cause some diseases and is a risk factor for others, disease also adversely affects nutrition: it directly contributes to malnutrition by reducing appetite, interfering with the absorption of nutrients, or altering the metabolism and increasing nutrient demand, and it indirectly aggravates malnutrition by causing the loss of nutrients through vomiting, diarrhea or bleeding (Horton 2009; Black 2008; WFP 2007; Allen et al. 2006; WHO 2004). In as far as a poor health environment, infestation with parasites and lack of clean water and sanitation lead to blood loss and diseases like diarrhea, they also contribute to nutrient deficiencies (Behrman and Deolalikar 1990; Block 2002; Ramakrishnan and Yip 2002; WHO 2004; WFP 2007; Kandpal and McNamara 2009).

Finally, the past focus of agronomists and policy makers on yields – thereby neglecting the nutritional quality of the crops – is also seen to be partly responsible for mineral malnutrition in humans (Welch and Graham 2000; 2002; Khoshgoftarmanesh et al. 2009). Reviewing a number of recent studies, White et al. (2009) confirm that increased yields in modern cultivars are often associated with reduced concentrations of minerals in edible crops, i.e. when grown under identical conditions, mineral concentrations are lower in genotypes yielding more grain or shoot biomass than in older, lower-yielding genotypes. One such negative trend in mineral concentrations is for instance depicted in Fig 3 for a historical set of wheat cultivars (*Triticum* spp.) that were released by CIMMYT between 1950

Fig. 3 Fe and Zn concentrations in wheat cultivars (Monasterio and Graham 2000)



and 1992 – a time during which grain yield has increased considerably. Similarly, Cakmak et al. (2000) found higher *Fe* and *Zn* concentrations in primitive wheat cultivars than in modern varieties (*Triticum* spp).

Another reason for low mineral concentrations in crops can be mineral deficient soils (e.g. see Bouis 2000, White and Broadley 2009). For instance the occurrence of ZnD in humans is correlated with areas where soils are deficient in plant-available *Zn*, as is the case in many Asian countries (Cakmak 2009a). Khoshgoftarmanesh et al. (2009) list in more detail mineral deficiencies in soils around the world; they also point out that micronutrients have been depleted from soils through higher crop production per unit area (when and where micronutrient fertilization was disregarded).

Interventions against mineral malnutrition

Conventional and novel, agricultural approaches

Given the negative impact of mineral malnutrition in humans on their individual well-being, social welfare and economic productivity, and given the various causes of mineral malnutrition mentioned in the previous section, various interventions to control mineral malnutrition have been devised. These interventions can be divided into three broad groups, namely supplementation, fortification and dietary diversification, which are complemented by the promotion of proper infant feeding practices, overarching nutrition education (especially of women), and supporting interventions in public health (like control of parasites and infectious diseases), water and sanitation, and more general poverty reduction Table 3 provides a tentative conceptual framework for categorizing individual interventions according to these broad groups (although the boundaries can be somewhat blurred when e.g. a capsule taken with lunch counts as supplementation but a powder sprinkled over the lunch counts as fortification).

Table 3 is also indicative of a trade-off between the possible speed and directness of the impact of the interventions and their long-term sustainability: interventions at the top can be implemented more quickly and the mineral dose provided can be adjusted more precisely, whereas towards the bottom more time is required to implement the intervention successfully (whether it is to breed and disseminate mineral-rich crops or to educate people and bring about behavior change). However, once implemented the interventions towards the bottom have a more enduring impact (mineral-rich seeds are replanted from the previous harvest and new behavior patterns persist) whereas e.g. the impact of supplementation ends after the last supplement was taken. Together, these interventions represent the toolbox for mineral interventions in public health and it becomes clear that each of them has its particular strengths and weaknesses (regarding time horizon,

Table 3. Overview of micronutrient interventions

Intervention	Description
Supplementation	*Supplying micronutrients in addition to people's usual dietary intakes*
Medical supplementation	Distribution of micronutrients in pharmaceutical form by medical staff or on prescription, often during routine health checks (especially iron pills for pregnant women), during specific supplementation campaigns or in combination with vaccination days (especially vitamin A doses for children)
Dietary supplementation	Selling of micronutrients as over-the-counter drugs, especially for self-medication in industrialized countries
Fortification	*Increasing micronutrient content and availability in the usual food people eat*
Home fortification	Addition of (commercial) micronutrient "sprinkles" during food preparation at home, often containing multiple micronutrients
Industrial fortification	Mandatory or commercial addition of micronutrients to foodstuffs during processing or (as premix) along the supply chain, for instance iodization of salt or enrichment of wheat flour with iron
Fertilization	Addition of minerals in (commercial or subsidized) fertilizers during crop cultivation to increase the mineral content in the final produce
Biofortification	Breeding crops (conventionally or through genetic engineering) to accumulate micronutrients in their edible parts (e.g. iron-rich rice or "golden rice"); also breeding crops for lower presence of micronutrient inhibitors (like phytate) in their edible parts
Dietary diversification	*Increasing the micronutrient uptake through different food*
Micronutrient-rich crops	Increasing production of micronutrient-rich crops (through agricultural policies or the promotion of home gardens) or increasing demand for micronutrient-rich food (through communication for behavior change)
Micronutrient availability in meals	Avoidance of micronutrient losses in food (through new food conservation and preparation techniques) or improvement of the bioavailability of the micronutrients that are present in a meal (through selection of food containing promotors and avoidance of food containing inhibitors of micronutrient uptake, e.g. including a vitamin C source or avoiding tea when consuming iron-rich food)
Infant feeding	*Promoting breastfeeding and proper weaning practices to avoid child malnutrition*
Nutrition education	*Overarching measure to generate the awareness and the knowledge to demand, put into practice and use the other interventions*
Public health measures; water, sanitation & hygiene; poverty reduction	*Supporting interventions to avoid micronutrient losses (e.g. through diarrhea or parasitic blood loss) and to generate the purchasing power to realize the demand for the other interventions*

dose adjustment, infrastructure needs, resource use, required intensity of cooperation of beneficiaries, etc.). Therefore there is no panacea, i.e. no intervention is "best" in all situations. Rather, policy makers have to decide on the right mix of interventions in each case.

Most of the interventions against mineral malnutrition lie outside the sphere of agronomy and are already discussed to various degrees elsewhere (e.g. GAIN 2009; Horton et al. 2008; WFP 2007; Stein 2006; MI/UNICEF 2004; Allen 2003b; Kennedy et al. 2003a; Kennedy et al. 2003b; WHO 2002; Ruel 2001; FAO 2001; Underwood and Smitasiri 1999). However, interventions like increasing the micronutrient content in people's food through breeding crops for higher micronutrient content or through fertilizing crops with minerals (on mineral-poor soils), are interventions that fall squarely into the remit of plant and soil scientists. Moreover, agricultural approaches to increase the micronutrient content of food crops, in particular the use of genotypic crop variations in the uptake and accumulation of micronutrients, are also considered to be both (i) useful to overcome micronutrient deficiency in soils as a limiting factor in crop productivity and (ii) sustainable and cost-effective methods for alleviating mineral deficiency in humans (Khoshgoftarmanesh et al. 2009).

The plant breeding approach is called (genetic) "biofortification" and its major advantage comes from the fact that the diets of the target populations (i.e. the poor and malnourished, especially in rural areas) are based primarily on a few staple crops that are eaten regularly in larger amounts by all family members. Hence biofortification is self-targeting. This is also an important difference to industrial fortification that may bypass the poor who lack the purchasing power to buy processed food – as it may bypass households in remote rural areas if they are self-sufficient or have no direct access to outlets where processed food is sold. Another major advantage of biofortification is economics. After an initial investment into the development of the germplasm, recurrent costs are low: the germplasm can be shared internationally and, once adopted by farmers, the seeds can be saved and biofortified crops can be cultivated year after year, thus allowing the realization of economies of scale across space and time that make the biofortified crop system highly sustainable. Finally, biofortification with minerals may be synergetic in that it not only improves the nutritional value of the crops but also – in as far as the mineral is also essential for the plant – the vigor of the seeds and the plant itself, thus avoiding a yield penalty (for an overview see Nestel et al. 2006; Graham et al. 2001; Welch and Graham 2002).

The challenges plant breeders are confronted with – stability of nutrient efficiency, reliability of screening techniques, impact on crop yields, concentration of toxic metals, bioavailability of micronutrients – are reviewed by Khoshgoftarmanesh et al. (2009) and to some extent Welch and Bouis (2009). Nevertheless, it has already been established since years that biofortification of key crops is feasible in principle (Graham et al. 1999; see also White and Broadley

2005). First intervention studies and feeding trials have already shown that biofortified crops can indeed improve the micronutrient status of their consumers (Haas et al. 2005; Low et al. 2007; Rosado et al. 2009; Tang et al. 2009) and a sensory analysis study has confirmed that mineral biofortification is possible without significant sensory differences between biofortified crops and controls (Park et al. 2009).

The fertilizer approach (also called "agronomic" biofortification), while sharing the advantage of biofortification to be self-targeting if applied to staple crops, has the drawback that it requires a system for the regular and widespread distribution of the fertilizer – which may again exclude poor farmers or those living in remote rural areas. Moreover, the need to apply fertilizer regularly eliminates the economic advantage of biofortification, i.e. the possibility to exploit economies of scale over space and time. Similarly, the fertilizer may not be used by all target farmers if it is not subsidized or otherwise made accessible to them. However, in places where mineral malnutrition is prevalent and where there is already an established infrastructure or fertilizer use is widespread, minerals could be added to conventional fertilizer and thus achieve a quicker impact than would be possible with biofortification (for further discussions of this approach see Broadley et al. 2006; Cakmak 2008; White and Broadley 2009; Cakmak 2009a; Cakmak 2009b; Welch and Bouis 2009. Martínez-Ballesta et al. 2009 discuss the fertilizer approach also in the context of environmental stress that affects plant mineral content. Khoshgoftarmanesh et al. 2009 provide a comprehensive review of possible agricultural approaches – including soil and foliar fertilization, crop systems, application of soil amendments and organic sources, as well as biofortification – to address micronutrients deficiency and to increase micronutrient density in the edible parts of plants. For a comparison of biofortification and fertilization see also Zhu et al. 2007).

Currently no in-depth studies on impact and cost-effectiveness of the fertilizer approach are available (although in a recent review Martínez-Ballesta et al. (2009) suggest that fertilization is one of the most practical and effective ways to improve the nutritional value of crops). However, for biofortification of various staple crops a number of ex-ante analyses have already shown the potential of this approach to considerably reduce micronutrient malnutrition in a very cost-effective manner (also compared to other micronutrient interventions), whether through classical breeding or genetic engineering and whether biofortification is done with Fe, Zn or beta-carotene (Zimmermann and Qaim 2004; Stein et al. 2006, 2007, 2008a, 2008b; Meenakshi et al. 2009; Table 4). A recent report by the UK's Royal Society on science and the sustainable intensification of global agriculture also acknowledges that the introduction of biofortified varieties may offer a solution to micronutrient malnutrition (Baulcombe et al. 2009).

Most of the biofortified crops are currently being developed in the framework of a few international programs, but also of more limited or more recent research

Table 4 Projected impact and cost-effectiveness of mineral biofortification and benchmarks (Meenakshi et al. 2009; Qaim and Stein 2009; Stein et al. 2008a; Ma et al. 2008; Stein et al. 2007; Stein and Qaim 2007)

Mineral	Crop	Country	Burden of disease of respective deficiency		Cost per DALY saved (USD)*	
			high impact scenario	low impact scenario	high impact scenario	low impact scenario
Fe	Rice	Bangladesh	-21%	-8%	3	10
		Philippines	-11%	-4%	49	197
		India	-38%	-12%	4	<1
	Wheat	India	-26%	-7%	9	<1
	Beans	NE-Brazil	-36%	-9%	13	56
		Honduras	-22%	-4%	20	114
Zn	Rice	Bangladesh	-46%	-15%	2	6
		Philippines	-39%	-11%	7	46
		India	-41%	-18%	4	<1
	Wheat	India	-12%	-2%	40	2
	Beans	NE-Brazil	-20%	-5%	95	799
		Honduras	-15%	-3%	48	423
Fe, Zn	Rice, wheat	China	-57%	-18%	4	14

* A World Bank threshold for highly cost-effective interventions is 200 USD/DALY saved, whereas other standard valuations of one DALY (in cost-benefit analyses in developing countries) are often based on per capita incomes or approximations thereof (e.g. 1,000 USD). Cost-effectiveness estimates of the WHO for supplementation and fortification with iron and zinc falls into the range of 2-487 USD/DALY saved.

projects that cover specific micronutrients, crops or regions:

- HarvestPlus, a "Global Challenge Program" of the Consultative Group on International Agricultural Research (CGIAR), focuses on those staple crops it has identified as being most important in the diets of the poor and malnourished in developing countries, namely rice, wheat, maize, cassava, sweet potatoes and beans. These crops are conventionally bred for higher levels of Fe, Zn and beta-carotene (HarvestPlus 2009).
- The "Golden Rice Project" focuses on rice only, and in contrast to HarvestPlus it follows a genetic engineering approach to biofortify rice with beta-carotene and, more recently under the "Grand Challenges in Global Health" scheme of the Bill & Melinda Gates Foundation, also with Fe, Zn, vitamin E and protein (GR 2009).
- Other projects that are also sponsored by the Gates Foundation are the

"African Biofortified Sorghum Project" where the goal is to biofortify sorghum with Fe, Zn, vitamin A and vitamin E (ABS 2009), the "BioCassava Plus" project that targets Fe, Zn, vitamin A, vitamin E and protein (BCP 2009), and a project for the biofortification of bananas with Fe, provitamin A and vitamin E (GCGH 2009).

- Smaller research projects, some of which also target micronutrient malnutrition in industrialized countries, cover for instance the biofortification of cereals, carrots, lettuce, brassica, tomatoes or potatoes with Se, Ca, Mg, folate or essential amino acids, or they try to reduce the accumulation of toxic analogues of the targeted mineral (cadmium (Cd) instead of Zn) (Broadley et al. 2006; Zhu et al. 2007; Zhu et al. 2009; Connolly 2008; Ríos et al. 2008; Bekaert et al. 2008; Palmgren et al. 2008; Stomph et al. 2009; Broadley et al. 2009). Of these projects probably the BAGELS project at the University of Nottingham, which aims at the fortification of wheat with Se, is furthest advanced (BAGELS 2009).
- Last year INSTAPA, a project funded by the 7th Framework Programme of the European Union, started with the aim of identifying novel staple food-based approaches (incl. biofortification) to address FeD, ZnD and VAD; its target groups are women and children in sub-Saharan Africa and it focuses on the improvement of (complementary) foods based on millet, sorghum, maize and cassava (INSTAPA 2009).
- "Harvest Zinc" is another recently initiated project, which focuses on the fertilizer approach (Cakmak I 2009b); the target crops of this project are cereals and the goal is to increase their Zn content (Harvest Zinc 2009).

Current developments and constraints

Despite the flurry of research activities, most biofortified crops are still at the stage of research and development; only orange-fleshed sweet potatoes are already introduced and promoted in Africa. Hence more general statements on the determinants of the adoption of mineral biofortified crops by farmers and on their acceptance by consumers (who can be the same farmers) are difficult to make. While it is assumed that mineral biofortification does not change visible crop characteristics (unlike the change in color introduced through beta-carotene biofortification), if the biofortification is done through genetic engineering and if food from genetically modified (GM) crops needs to be labeled, mineral biofortified crops may also become differentiable from conventional crops. In this case farmers as well as consumers have to decide actively in favor of biofortified crops for the latter to have an impact on mineral malnutrition.

Various studies on the acceptance and on potential barriers to the adoption of noticeably biofortified crops have been carried out (Chowdhury et al. 2009; Stevens and Winter-Nelson 2008; Muzhingi et al. 2008; De Groote et al. 2008;

Dickinson et al. 2008; Heyd 2007; Wolson 2007; Pray et al. 2007; Mazuze 2007; Chong 2003; Hagenimana and Low 2000). These studies indicate that, above all, biofortified crops have to have agronomic properties of interest to farmers (e.g. higher yields, drought tolerance, propagation capacities or pest resistance), they have to be available as locally adapted varieties and access to the planting material has to be easy and reliable. Biofortified crops also have to be marketable so the farmers can sell them for income generation if necessary, i.e. there have to be markets nearby and the crops have to be acceptable to consumers, i.e. they have to correspond closely to familiar varieties, especially regarding taste and consistency but also regarding storability. Furthermore, community-based participatory approaches to research and product development that ensure the identification of the genotypes that best suit producer-consumer needs, improvement of women's access to corresponding resources and accompanying nutrition information tend to speed up adoption and increase consumer acceptance, inducing even a positive willingness to pay for biofortified crops. If these conditions are or can be fulfilled it seems possible to ensure sufficiently widespread acceptance also of such recognizably biofortified crops (Nestel et al. 2006; Qaim et al. 2007; Qaim and Stein 2009). And indeed, in the CGIAR proposal for its biofortification program the centers involved clearly highlight the need to avoid bypassing the rural poor, they stress the need to pay attention to seed multiplication and diffusion, and they suggest collaborating with national agricultural research extension systems, commodity-based regional research networks, local and private companies, civil society groups, farmers organizations, women's cooperatives and specially-formed seed producer groups, supporting a mix of centralized and decentralized seed production and diffusion arrangements to ensure a steady supply of the new germplasm that meets farmer-desired quality standards (CIAT/IFPRI 2002).

In the case of biofortification through genetic engineering additional problems may prevent the biofortified crops from reaching farmers and consumers in the first place. For instance (to refer to the most advanced biofortified GM crop), when Golden Rice was developed, the complexity resulting from fragmented intellectual property ownership was considered to represent a potential constraint for its commercial development (Delmer et al. 2003; Kryder et al. 2000). However, as one of its developers highlights, compared to the hurdles raised by the regulatory requirements for GMOs that Golden Rice has to comply with, the issue of sorting out the intellectual property rights (IPR) was only a minor one (Potrykus 2009). According to Potrykus, current GMO regulation delays the introduction of GM crops by years and imposes a heavy financial burden on their developers – with the consequence that public institutions cannot afford to commercialize humanitarian crops (and that only a few financially potent companies remain that concentrate on the development of a few profitable crops for selected lucrative markets). Similarly Cohen and Paarlberg (2002) point out that IPR constraints are real but not a primary reason for the unavailability of GM crops for poor country farmers: on the one hand patents lack international protection and can only be enforced where they were granted and developing country governments have other political and legal means to obtain needed licenses, on the other hand in the past private companies have shown to be ready to extend their proprietary GM technologies into the developing world and to waive royalties on the use of their IPR for humanitarian purposes.

Related to the strict regulation of GMOs, another barrier that may prevent developing countries from cultivating or even approving GM crops is the fear of commercial losses in the form of lost export sales to Europe: because of critical consumers and restrictive import and labeling policies in importing countries, food exporting countries in the developing world are hesitant to implement biosafety frameworks and to approve GM crops (Cohen and Paarlberg 2002; Pray and Huang 2007). Given the possibility of adventitious "cross commingling" along the supply chain of one type of GM crops with other types of crops (Reuters 2009), fear of commercial losses may even hamper the approval of biofortified crops that are targeted at local markets – although studies indicate that developing countries are set to gain more from GM crops than they may loose (Paarlberg 2006, Anderson et al. 2004). Yet, at least for consumers in Asia, genetic engineering does not seem to be a major issue; they trust the authorities and are much more concerned about other food-related issues, like zoonoses, microbiological contamination, pesticide residues or food additives (Cairns 2005).

Conclusions

This review of the impacts of mineral malnutrition in humans clearly shows that mineral malnutrition negatively affects billions of people and – through the often severe or even fatal health outcomes it produces – imposes a heavy burden on humankind and overall development by reducing individual well-being, social welfare and economic productivity at a large scale. While the underlying causes of micronutrient malnutrition are complex and sometimes mutually reinforce each other, one direct and immediate determinant of mineral malnutrition is insufficient dietary intakes. Consequently most current micronutrient interventions in the field of public health aim at adding the lacking minerals to people's diets (either by directly fortifying food or in the form of supplements). However, providing wholesome food is one of the key tasks for agronomists (Agronomist 2009), and while the more differentiated nutritional qualities of food may have been neglected in the past when the main concern were yields, new approaches to control mineral malnutrition also – and rightly so – rely on agricultural sciences to increase the micronutrient content in major staple crops. First studies have shown that breeding plants for higher mineral densities in the edible part of the crops

promises to be a very cost-effective intervention in the fight against micronutrient deficiencies. Crucially, as long as the other agricultural properties of the plants are not neglected, the adoption of biofortified crops by farmers is not compromised. In some cases (e.g. when sensory changes occur or when genetic engineering is used in the breeding process), particular emphasis on community-based approaches and the dissemination of nutrition information may become necessary to enhance the acceptance of biofortified crops by consumers. In the case of genetic engineering also the international community is called upon to help avoiding that strict regulations in rich export markets prevent poor countries from using a promising tool in the fight against micronutrient malnutrition.

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The opening of Pandora's Box: Climate change impacts on soil fertility and crop nutrition in developing countries

Samuel B St Clair • Jonathan Lynch

Abstract Feeding the world's growing population is a serious challenge. Food insecurity is concentrated in developing nations, where drought and low soil fertility are primary constraints to food production. Many crops in developing countries are supported by weathered soils in which nutrient deficiencies and ion toxicities are common. Many systems have declining soil fertility due to inadequate use of fertility inputs, ongoing soil degradation, and increasingly intense resource use by burgeoning populations. Climate models predict that warmer temperatures and increases in the frequency and duration of drought during the 21st century will have net negative effects on agricultural productivity. The potential effects of climate change on soil fertility and the ability of crops to acquire and utilize soil nutrients is poorly understood, but is essential for understanding the future of global agriculture. This paper explores how rising temperature, drought and more intense precipitation events projected in climate change scenarios for the 21st century might affect soil fertility and the mineral nutrition of crops in developing countries. The effects of climate change on erosion rates, soil organic carbon losses, soil moisture, root growth and function, root-microbe associations and plant phenology as they relate to mineral nutrition are discussed. Our analysis suggests that the negative impacts of climate change on soil fertility and mineral nutrition of crops will far exceed beneficial effects, which would intensify food insecurity, particularly in developing countries.

Keywords Drought • erosion • food security • precipitation • soil degradation • soil organic carbon • temperature

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Challenges to food security in developing countries in the 21st century

The world in general and developing countries in particular face major challenges of food security in the 21st century. Current estimates suggest that more than 1.02 billion people on our planet are underfed or malnourished including a 10% increase over the last 3 years due to rising food costs (FAO 2009). Food insecurity is increasing and projections are that it will worsen in coming decades. Demand for food is expected to increase 2-5 fold from 1990 to 2030, while per capita arable land area dedicated to crop production continues to shrink because of population growth, urbanization and soil degradation (Daily et al. 1998). Estimates suggest that food production will have to increase by 60% in the coming decades to meet world food demands (Wild 2003). The only way to keep pace with the demand will be to increase crop production by farming marginal lands, or through more intensive production on lands already under cultivation (Lal 2000). The green revolution is an excellent example of how agricultural intensification driven by innovation resulted in exponential increases in crops yields that kept pace with population growth in the mid 20th century (Borlaug 2007). Once again food production in developing countries is being outpaced by rapid population growth. From the supply side, this imbalance is largely driven by edaphic constraints that result from inherently low soil fertility and/or soil degradation from unsustainable farming practices (Lal 2007).

The success of the green revolution was mainly driven by dwarf crop varieties that could respond to fertilizer inputs without lodging. However, yield increases that kept pace with population growth during the green revolution have slowed since the 1990's (Fig. 1). The green revolution bypassed sub-Saharan Africa as crop yields were heavily constrained by nutrient poor soils and most farmers had little or no access to fertilizers. Africa is the only continent where cereal production per capita has steadily decreased since the early 1960's (Fig. 1).

Much of the research aimed at understanding best farming practices is focused on the challenges and crop species that are relevant to developed countries where the resource base exists for conducting research. Based on these challenges there has been a call for a second green revolution with a goal of enhancing crop yields in developing countries by improving soil fertility through better management practices (Sanchez and Swaminathan 2005) and by breeding crops with greater tolerance to edaphic stresses (Lynch 2007). There is substantial opportunity to improve crop yields since current production is only a fraction of yield potential (Lynch 2007) (Table 1). In addition, significant genetic variation exists for crop traits associated with tolerance to mineral stress, and biotechnological advances are accelerating the process of trait identification and selection (Lahner et al. 2003; Wu et al. 2008).

Nutrient impoverished soils contribute to human malnutrition in two

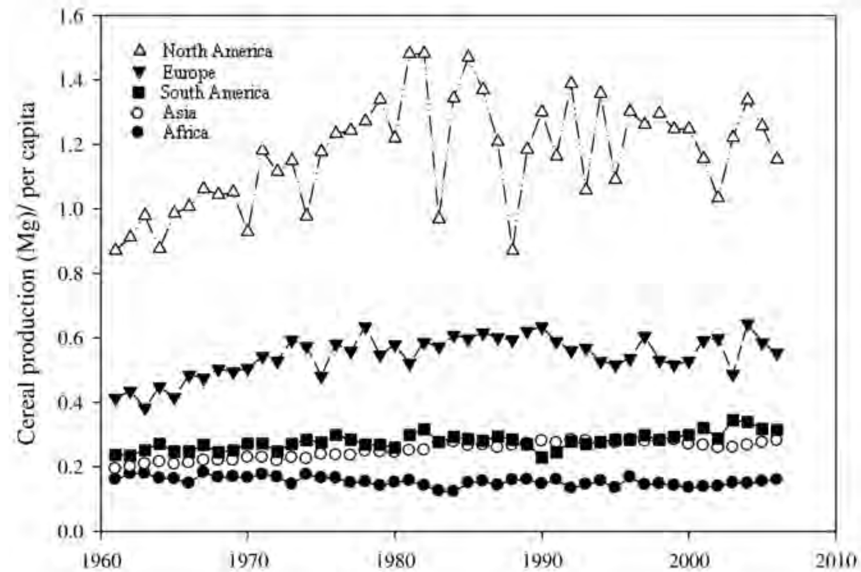


Fig. 1 Cereal production per capita from 1960-2008. Source: Food and Agriculture Organization of the United Nations (FAO). FAOSTAT 2009 (last updated June 23 2009).

important ways. First, they reduce crop yields, causing food scarcity that results in protein-energy malnutrition. Second, crops produced on nutrient poor soils typically have low tissue concentrations of trace elements. Human populations whose diet primarily consists of staple cereal crops (primarily maize, rice, wheat, sorghum, and millet) may meet their protein and energy demands but often suffer micronutrient deficiencies. It is estimated that of the world's human population, 60-80% are Fe deficient, >30% are Zn deficient, 30% are Iodine deficient and about 15% are Se deficient (White and Broadley 2005). The overwhelming majority of people that suffer from micronutrient deficiencies live in developing countries (Kennedy et al. 2003).

If we are somehow able to clear this first hurdle and increase crop yields and nutrient availability by overcoming soil limitations, global climate change also looms large in determining food sufficiency and quality in the 21st century (Rosenzweig and Parry 1994). Evidence suggests that due to high vulnerabilities and limited resources, developing countries may have limited capacity to implement adaptation measures to achieve food stability in a warmer climate (Kates 2000; Mertz et al. 2009). It is well documented that climate warming, and changes in global precipitation patterns, particularly drought, are already affecting crop production in developing countries (Pandey et al. 2007; Barrios et al. 2008).

Table 1 Average yield of staple crops from 2003-2005. [a]source: FAOSTAT, last update January 24, 2006 (Lynch 2007)

	Average Yield 2003-2005 (metric t ha^{-1})[a]					
	Maize	Bean	Rice (paddy)	Wheat	Sorghum	Millet
Africa, developing	1.4	0.6	2.0	2.2	0.85	0.68
Africa, developed	3.1	1.4	2.3	2.2	3.3	0.57
Asia, developing	4.0	0.6	4.0	2.9	1.0	1.0
Asia, developed	15.9	2.0	6.3	3.6	2.9	1.0
Latin America and Carribean	3.3	0.8	3.9	2.6	3.0	1.7
Latin America, developed	10.8	1.9	4.8	4.4	-	-
Developed Countries (world)	7.8	1.7	6.5	2.9	3.7	1.3
United States	9.4	1.8	7.5	2.9	4.0	1.3
Yield potential with high water and nutrient input	20[b]	5.8[c]	10[d]	10[e]	4.0[f]	4.3[g]

Africa, developed: South Africa; Asia, developed: Japan, Israel; Latin America, developed: Chile; World developed: Albania Armenia, Australia, Austria Republic of Azerbaijan, Belarus, Belgium, Luxembourg, Bosnia and Herzegovina, Bulgaria, Canada, Croatia, Czech Republic, France, Georgia, Germany, Greece, Hungary, Israel, Italy, Japan, Kazakhstan, Kyrgyzstan, Luxembourg, Macedonia, Moldova, Netherlands, New Zealand, Poland, Portugal, Romania, Russian Federation, Serbia and Montenegro, Slovakia, Slovenia, South Africa, Spain, Switzerland, Tajikistan, Turkmenistan, Ukraine, United Kingdom, United States of America, Uzbekistan. [b]Tollenaar and Lee (2002); [c]Beaver et al. (2003); [d]Peng et al. (1999); [e]Tripathi et al. (2004); [f]Baumhardt et al. (2005); [g]van Oosterom et al. (2003).

An important but poorly understood effect of climate change is its influence on soil fertility and nutrient acquisition and utilization by plants (Lynch and St Clair 2004). The first objective of this paper is to provide an overview of what we view as the two most important environmental impediments to food security in developing countries in the 21st century: soil degradation and climate change. We will focus our discussion on the three continents (Asia, Africa and South America) with the largest number of developing countries because that is where the vulnerabilities and knowledge gaps are the greatest. With that foundation, our central objective is to synthesize our current understanding of how climate change is likely to affect crop nutrient acquisition and utilization in soils of the developing world. Interactions between climate and soil resource availability and their influence on crop function and attendant yields are complex and this paper will not attempt a comprehensive exploration of these topics. Instead we will examine how rising temperature, drought and intense precipitation events (the three most important climate variables) are likely to influence nutrient acquisition by crop plants. Finally, we will explore: 1) various adaptation measures that are most likely to be effective in stabilizing crop yields grown under suboptimal soil conditions in future climates; and 2) impediments to their implementation.

Soil limitations to crop productivity in developing countries

Edaphic stresses are so common in soils of developing countries that it has been estimated that on average less than a third of them are free from constraints that significantly reduce crop yields (Lal 2000) (Table 2). Inherently poor soil conditions are a contributing factor to food insecurity and malnutrition, the biggest risk factor for human illness and disease (Sanchez 2002; Sanchez and Swaminathan 2005). Most developing countries exist in tropical or sub-tropical climates with weathered soils including Oxisols, Ultisols, and Alfisols that are characterized by low phosphorus and nitrogen availability, and soil acidity which is often associated with deficiencies of calcium, magnesium and potassium and toxicities of Al and Mn (Sanchez 1976). Soils in the semi-arid and arid subtropics include Aridisols, Inceptisols, Entisols and Vertisols and are prone to deficiencies in P and micronutrient transition metals (Fe, Cu, Mn, and Zn). It is estimated that as much as 50% of irrigated land world wide is affected by salinity stress (Flowers et al. 1997), which reduces crop yields in arid and semi-arid regions.

Physical soil constraints also significantly reduce crop yield potential in developing countries. They include poor soil texture, rockiness, compaction (Lal 1987), and slope steepness (Lal 1998). These physical soil characteristics determine the water holding capacity of the soil, the degree of root contact with the soil matrix and cation exchange capacity, all of which influence plant nutrient acquisition (Marchner 1995). The inherent limitations that are common in the soils of developing countries are exacerbated by unsustainable management practices that further degrade soil fertility and function (Table 2). It is estimated that 80% of

Table 2 Soil edaphic conditions and land degradation that place major constraints on crop yields. Source: Food and Agriculture Organization of the United Nations (FAO). TERRASTAT 2009

	% Soil w/ major constraints	%Land degradation
Africa	85	77
Asia	70	74
Australia	81	61
Europe	69	91
North America	73	49
South America	81	78

soil degradation worldwide occurs in developing countries (Lal 2000). Erosion driven by tilling practices and cultivation on sloped terrains is the most ecologically and economically devastating soil degrading process (Ananda and Herath 2003; Meadows 2003). In developing countries erosion can carry away as much as 30-40 t/ha/yr of topsoil (Barrow 1991). Lost with erosion are the nutrients that are abundant in the cation exchange sites and organic fractions of the topsoil. Since most fertilizers are surface broadcast large proportions of fertilizer inputs (20-50%) are also lost through erosive processes (Pimentel 1996). Soil erosion studies in Africa have shown drastic reductions in crop yields (>65%) because the exposed sub-surface soils have much lower fertility and poorer physical characteristics than topsoil (Oyedele and Aina 2006; Salako et al. 2007).

Estimates are that the world has lost 55-90 Pg of soil organic carbon (SOC) through land conversion from natural to agricultural ecosystems (Ruddiman 2003). Soil organic carbon (SOC) is positively correlated with crop productivity (Olson and Janzen 1992). High SOC enhances soil water holding capacity, increases soil fertility through cation exchange and mineralization processes and improves soil structure (Lal 2006). Increasing SOC in degraded soils is therefore a major goal in efforts to renew fertility in degraded soils (Lal 2006). As SOC accumulates it produces a positive feedback in which better functioning soil produces more crop biomass that then increases organic matter inputs to the soil (Lal 2006). Additionally, SOC storage is an important terrestrial sink for CO_2, which mitigates climate change (Post and Kwon 2000; Yu et al. 2009). In contrast, when SOC is lost through erosion, tillage and other agricultural processes (Lal 2004), soil function and plant productivity that maintains organic matter in the soil are compromised. Soil conditions, particularly soil moisture content, temperature and nutrients status have drastic effects on the abundance, infection potential and efficiency of N-fixing bacteria that are vitally important to increasing N in cropping systems that lack fertilizer inputs (Dakora and Keya 1997). Alleviation of soil constraints that are common in Sub-Saharan Africa dramatically increases nodulation, plant growth and crop yields, indicating that soil conditions represent a major limitation to biological N fixation (Dakora and Keya 1997).

Climate change impacts on crop productivity and quality in developing countries

Climate conditions, particularly drought, have had significant impacts on crop yield reductions and food insecurity in Africa over the last 50 years (Barrios et al. 2008). Analyses suggest that this trend will intensify in developing countries during the 21st century (Murdiyarso 2000; IPCC 2007b). During the 20th century Asia, Africa and South America experienced a 0.7-1.0 °C increase in temperature (IPCC 2007a). Conservative estimates from climate models suggest that by the

end of the 21st century, temperature averages on those continents will have increased by at least another 2-4 °C (Salinger 2005; IPCC 2007a). Subtropical regions are likely to experience increases in drought which will be driven by higher vapor pressure deficits and less annual rainfall (Shindell et al. 2006; IPCC 2007a). Variability in precipitation patterns are projected to increase with longer periods of droughts interspersed with more intense rainfall events (Easterling et al. 2000; Groisman et al. 2005; Sun et al. 2007). These changes in temperature and precipitation are expected to have net negative effects on global agriculture and in particular in developing countries (IPCC 2007b). The severe impacts of drought on crop failure that has led to widespread starvation in sub-Saharan Africa during the late 20th century is expected to continue and intensify in the 21st century (Broad and Agrawala 2000; Held et al. 2005). By 2020, yields from rain-fed agriculture in Africa could be reduced by 50%, largely a result of increases in the intensity and duration of drought events (IPCC 2007b). Depending on location, increases in the frequency and magnitude of droughts and floods are expected to have major impacts on agricultural production in Asia (IPCC 2007b). Recent climate models suggest that future patterns of drought in Asia are likely to be most problematic in Asian monsoon regions (AMRs: South Asia and East Asia) and West Asia during the spring and summer months (Kim and Byun 2009). In South America, shifts in precipitation patterns and the disappearance of glaciers are expected to substantially decrease water availability for agriculture. Projected warming and reductions in precipitation expected to occur by 2030 in developing countries, suggests that South Asia and Southern Africa will be the two regions most likely to suffer negative impacts on several crops important to large food-insecure populations (Lobell et al. 2008).

Recent analysis suggest that uncertainty in understanding crop responses to future climate change is greater for temperature than precipitation (Lobell and Burke 2008). The influence of warmer temperatures on crop yields will somewhat depend on moisture availability. In areas where precipitation is plentiful or irrigation is available, warmer temperatures may positively influence yields by: 1) increasing rates of physiological capacity (Taiz and Zeiger 2006); 2) lengthening the growing season (Juin et al. 2004); and 3) reducing the incidence of frost damage to crops in temperate climates (Moonen et al. 2002). In semi-arid and arid regions, the largest impact of warmer temperatures on agriculture will be exacerbation of soil moisture deficit (drought) driven by increased rates of evapotranspiration (Biggs et al. 2008). Interestingly, increases in both daily maximum and minimum temperatures (which will continue to rise during the 21st century) have been shown to negatively impact crop yields, by altering phenology (Mitchell et al. 1993; Peng et al. 2004) and through heat stress at more extreme temperatures (Spiertz et al. 2006).

Soil moisture is the master environmental variable because its availability integrates climate and soil conditions, and because plants and soil microbes are so responsive to its availability. Drought is an important selection force on biological organisms (McDowell et al. 2008) and can drastically alter plant community structure and function (Ciais et al. 2005; Holmgren et al. 2006). One of the important innovations in human agriculture was irrigation which mitigated the negative impacts of water deficit on crop growth. However, because of the extent and magnitude of projected climate change, infrastructure, adaptation to drought in developing countries appears to be limited in the future (Kates 2000; De Wrachien and Feddes 2004).

In addition to the effects of climate on crop growth potential and yield, temperature extremes and water deficit can have varying effects on the nutritional quality of harvested products. Elevated temperature and drought tend to reduce grain yield and starch content, while increasing protein content (Gooding et al. 2003, Erekul and Kohn 2006). Temperature is positively correlated with grain micronutrient concentrations (Karami et al. 2009) and frost damage reduces grain filling and typically has negative effects on grain quality (Cromey et al. 1998; Allen et al. 2001). Elevated CO_2 generally increases grain size but reduces protein and mineral nutrient concentrations (Hogy and Fangmeier 2008), which may result from tissue dilution and/or reductions in transpiration-driven mass flow of nutrients (Lynch and St.Clair 2004). Post-harvest fruit and grain losses can be as high as 20% in developing countries (Aidoo 1993). Fruit and grain spoilage is particularly problematic in tropical areas where climate conditions are optimal for microbial growth. The effect of climate change on postharvest storage of crops is poorly understood but could be substantial in some regions.

Key climate-nutrient interactions in cropping systems of developing countries

Brouder and Volenec (2009) pointed out that: "implicit in discussions of plant nutrition and climate change is the assumption that we know what to do relative to nutrient management here and now but that these strategies might not apply in a changed climate." In other words, the rate and magnitude of changes in precipitation and temperature, anticipated in the coming century have the potential to fundamentally alter our understanding and strategies for the nutrient management of crops.

Drought effects on nutrient acquisition

Crop yields on soils in developing countries decrease exponentially with increasing aridity (Lal 2000). Soil moisture deficit directly impacts crop

productivity but also reduces yields through its influence on the availability and transport of soil nutrients (Table 3). Drought increases vulnerability to nutrient losses from the rooting zone through erosion (Gupta 1993). Because nutrients are carried to the roots by water, soil moisture deficit decreases nutrient diffusion over short distances and the mass flow of water-soluble nutrients such as nitrate, sulfate, Ca, Mg, and Si over longer distances (Mackay and Barber 1985; Barber 1995). Roots extend their length, increase their surface area and alter their architecture in an effort to capture less mobile nutrients such as phosphorus (Lynch and Brown 2001). Reduction of root growth and impairment of root function under drought conditions thus reduces the nutrient acquisition capacity of root systems (Marchner 1995).

Drought also disrupts root-microbe associations that are a principal strategy for nutrient capture by plants. Reductions in both carbon and oxygen fluxes and nitrogen accumulation in root nodules under drought conditions inhibit nitrogen fixation in legume crops (Gonzalez et al. 2001; Ladrera et al. 2007; Athar and Ashraf 2009). Drought alters the composition and activity of soil microbial communities which determine the C and N transformations that underlie soil fertility and nutrient cycling (Schimel et al. 2007). For example, soil moisture deficit has been shown to reduce the activity of nitrifying bacteria by slowing diffusion of substrate supply and through cytoplasmic dehydration (Stark and Firestone 1995). Less is known about how drought influences mineralization and decomposition in agricultural systems but it likely slows these processes. Studies suggest that the root-mycorrhizal symbiosis is not overly sensitive to moderate soil moisture deficits (Entry et al. 2002; Garcia et al. 2008). There is a large literature documenting the beneficial effects of mycorrhizal fungi in crops plants experiencing drought conditions (Wu and Chang 2004; Boomsma and Vyn 2008). Part of the benefit provided by mycorrhizae under drought conditions is associated with increase in nutrient transfer to the roots (Goicoechea et al. 1997; Al-Karaki and Clark 1998).

Effects of Intense precipitation on nutrient acquisition

Excessive precipitation can reduce crop yields (Paul and Rasid 1993; Kawano et al. 2009) (Table 3). Intense rainfall events can be a major cause of erosion in sloped cropping systems and where soil instability results from farming practices that have degraded soil structure and integrity (Meadows 2003). Surface erosion during intense precipitation events is a significant source of soil nutrient loss in developing countries (Tang et al. 2008; Zougmore et al. 2009). Because of its high mobility in soil, nitrate leaching following intense rainfall events can also be a significant source of N loss in agriculture (Sun et al. 2008).

Table 3 Potential interactions of global change variables with mineral stress discussed in the text

Process	Global change variables	Interaction with mineral stress
Erosion	heavy precipitation, drought	general losses of soil nutrients, SOC and fertilizer
Transpiration-driven mass flow	drought, temperature, RH, CO_2	NO3, SO4, Ca, Mg, and Si
Root growth and architecture	drought, soil temperature, CO_2	All nutrients, especially P and K
Mycorrhizas	CO_2	P, Zn (VAM) N (ecotomycorrhizas)
Soil microbes (N cycling)	drought, soil temperature	N N
Biological N Fixation	drought, soil temperature	
Soil redox status	flooding	Mn, Fe, Al and B
Soil leaching	heavy precipitation	NO3, SO4, Ca, Mg
Plant phenology	temperature	P, N, K
Soil organic carbon status	soil moisture, soil temperature, CO_2	all nutrients
Salinization	precipitation, temperature	Na, K, Ca, Mg

Agricultural areas with poorly drained soils or that experience frequent and/or intense rainfall events can have waterlogged soils that become hypoxic. The change in soil redox status under low oxygen can lead to elemental toxicities of Mn, Fe, Al and B that reduce crop yields (Setter et al. 2009), and the production of phytotoxic organic solutes that impair root growth and function (Marchner 1995). Hypoxia can also result in nutrient deficiency since the active transport of ions into root cells is driven by ATP synthesized through the oxygen dependent mitochondrial electron transport chain (Drew 1988; Atwell and Steer 1990). Significant nitrogen losses can also occur under hypoxic conditions through denitrification as nitrate is used as an alternative electron acceptor by microorganisms in the absence of oxygen (Prade and Trolldenier 1990; Marchner 1995).

Effects of temperature on nutrient acquisition

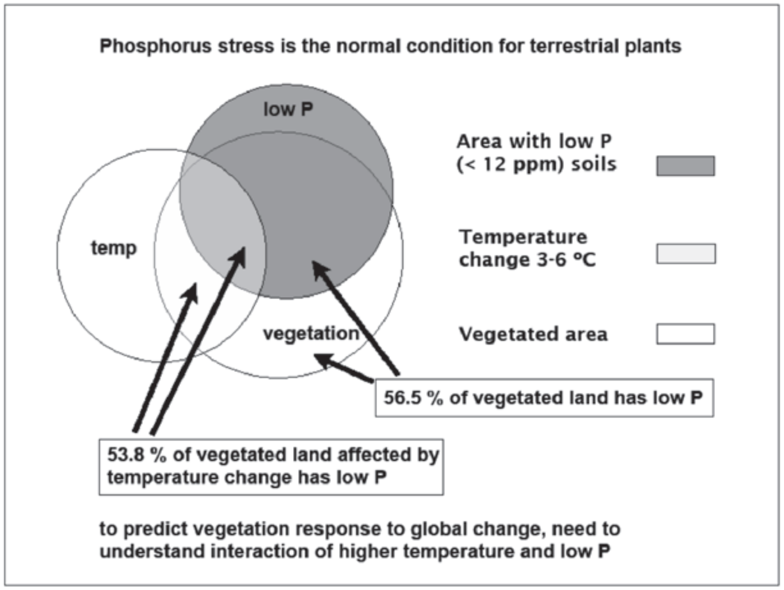
Soil warming can increase nutrient uptake from 100-300% by enlarging the root surface area and increasing rates of nutrient diffusion and water influx (Ching and Barber 1979; Mackay and Barber 1984) (Table 3). Water soluble nutrients including nitrate, sulfate, Ca, Mg primarily move towards roots through transpiration-driven mass flow (Barber 1995). Since warmer temperatures increase rates of transpiration, plants tend to acquire water soluble nutrients more readily as temperature increases. Temperature increases in the rhizosphere can also stimulate nutrient acquisition by increasing nutrient uptake via faster ion diffusion rates and increased root metabolism (Bassirirad 2000). However, any positive effects of warmer temperature on nutrient capture are dependent on adequate soil moisture. If under dry conditions higher temperatures result in extreme vapor pressure deficits that trigger stomatal closure (reducing the water diffusion pathway in leaves) (Abbate et al. 2004), then nutrient acquisition driven by mass flow will decrease (Cramer et al. 2009). Temperature driven soil moisture deficit slows nutrient acquisition as the diffusion pathway to roots becomes longer as ions travel around expanding soil air pockets (Brouder and Volenec 2008).

Emerging evidence suggests that warmer temperatures have the potential to significantly affect nutrient status by altering plant phenology (Nord and Lynch 2009). The duration of plant developmental stages is extremely sensitive to climate conditions and is particularly responsive to temperature (Cleland et al. 2007). Experimental warming was shown to shorten phenological stages in wheat that resulted in a 9% yield decrease per 1 °C increase in temperature (Mitchell et al. 1993). Nord and Lynch (2008) found that genotypes with shorter vegetative growth phases (shortened phenology) had ~30% decreases in reproductive tissue and seed production in soil with low phosphorus availability because of reduced P acquisition and utilization (Nord and Lynch 2008). This interaction between warming and P acquisition through shifts in plant phenology like other climate-nutrient interactions likely operate at a global scale (Fig. 2).

Because of the important role of SOC in enhancing soil moisture retention, fertility and structure, it has a disproportionately large impact on food security in developing countries (Lal 2006). Soil organic carbon stocks are the sum of soil organic inputs driven by plant productivity (root exudates, root and shoot turnover) and soil organic losses via heterotrophic respiration and erosion. Warmer temperatures can increase or decrease crop productivity and yield depending on crop type and agricultural zone (Singh et al. 1998). In the tropical and sub-tropical climates of most developing countries a 2-3 °C increase in temperature is expected to diminish crop productivity (Easterling and Apps 2005). Simulation models predict large losses in agricultural SOC over the 21st century resulting from lower crop productivity (inputs), and higher rates of heterotrophic respiration in response to climate warming (Jones et al. 2005; Smith et al. 2009). There is evidence that drier soils under warmer temperatures will also increase SOC losses via higher rates of wind erosion (Lee et al. 1996).

Climate warming contributes to the degradation of freshwater quality and

Fig. 2 Important climate-nutrient interactions often occur at a global scale. For example, this diagram illustrates that greater than 50% of the vegetated land area predicted to have significant increases in warming during the 21st century overlaps with low P soils. Recent studies suggest that climate warming hastens plant phenology, which is likely to exacerbate P deficiency in plants. Data from Jaramillo and Lynch, unpublished.



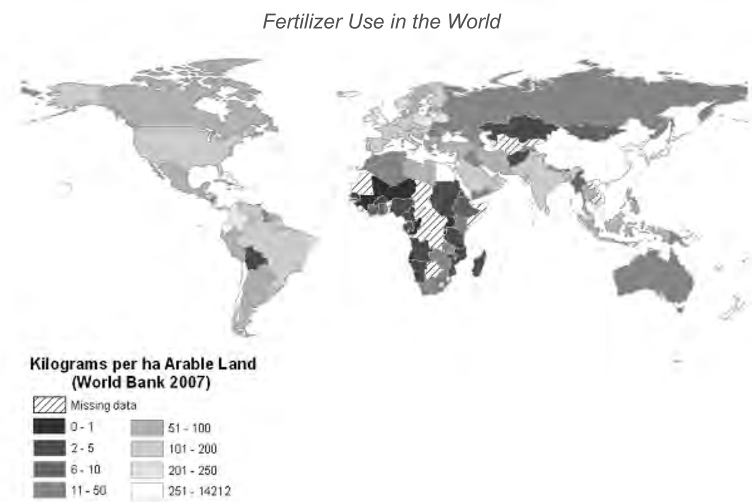
availability (IPCC 2007b). A major way in which this happens is through salinization, an important limitation to agriculture productivity in semi-arid regions that is expected to intensify through the 21st century (Yeo 1999). Increases in demand for irrigation in semi-arid regions such as the Indo-Gangetic plain of northern India and Pakistan and parts of Africa driven by population growth and climate warming are expected to increase the extent of salinization in agriculture (Yeo 1999). Climate warming can increase agricultural salinization by increasing the demand for irrigation and increasing rates of surface water evaporation. Warmer temperature can also increase salt accumulation in crops via increased transpiration rates (West 1980). Theoretically there are reasons to believe that elevated CO_2 may mitigate salt accumulation but empirical evidence does not support that conclusion (Yeo 1999, Nicolas et al. 1993). In addition, rising sea levels driven by climate warming is expected to contribute to seawater intrusion of coastal aquifers (Don et al. 2006; Antonellini et al. 2008).

Adaptation/mitigation strategies and limitations

The trends outlined above describe a dire situation that is likely to worsen in the short term. To address this challenge it is urgent that the fertility and productivity of agro-ecosystems in developing regions be maintained and even improved to keep pace with population growth. The conceptual framework for this effort should be integrated soil fertility management (ISFM), consisting of three primary components: 1) judicious use of fertilizers and soil amendments, 2) soil conservation to reduce erosion, maintain soil organic matter, and enhance water and nutrient bioavailability, and 3) cultivation of crop species, genotypes and cropping systems that make optimal use of soil resources for food production while conserving soil fertility.

Technically, the simplest solution to many of the fertility problems in low input agro-ecosystems would simply be to use fertilizers particularly in African nations where soil fertility is low and fertilizer use is minimal (Fig. 3). Indeed, the first Green Revolution consisted mainly of fertilizers and genotypes that could respond to them without lodging. Although many tropical soils have chemical characteristics that make fertilizer use problematic, the basic technologies for fertilizing tropical soils have been known for decades (Sanchez 1976), and demonstration plots have shown sustained yield improvements in response to liming and the application of chemical fertilizers (Sanchez et al. 1983; Fearnside 1987). In recent years private foundations have devoted considerable resources to

Fig. 3 World fertilizer use in 2007. Source: Food and Agriculture Organization of the United Nations (FAO). FAOSTAT 2009. Map produced by Raul Jaramillo



the improvement of fertilizer availability and use in sub-Saharan Africa as a key element of their programs to reduce world hunger.

These efforts notwithstanding, it is not obvious that application of chemical fertilizers will be sufficient or even successful over the broad spatial scales they are needed. Low input farmers typically do not have money to buy fertilizers, which are often considerably more expensive in poor countries than in wealthy nations because of poor transportation infrastructure and greater distances to the source of manufacture (Sanchez 2002). Even farmers that can afford fertilizers typically have poor access to distribution markets and limited information about how to properly use them. Local markets for goods and services are often dysfunctional because of corruption and lack of competition. In recent years, fertilizer costs have increased substantially along with energy costs, since fossil fuels are needed for fertilizer production and distribution. In the medium to long term, the cost of concentrated P fertilizer will increase as readily available phosphate ore deposits are depleted (Herring and Fantel 1993). Given the magnitude of these challenges, and the current trends in energy prices and sociopolitical stagnation in the poorest nations, it is doubtful that on a global scale, resource-poor farmers will be able to fertilize their way to higher yielding, more sustainable production systems in the next 10 or 20 years, a critical period in terms of resource degradation and hunger alleviation.

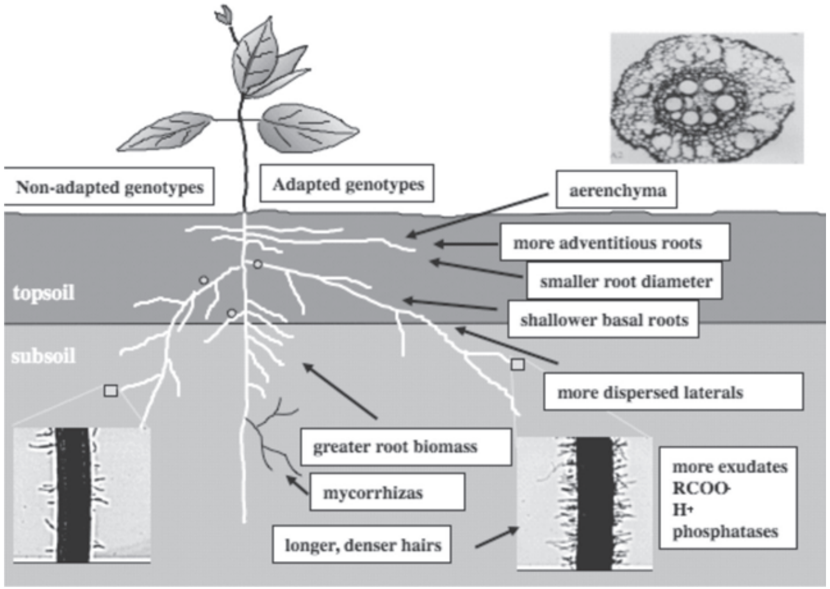
The use of locally available fertility amendments is a more feasible strategy for many poor farmers. These include minimally processed rock phosphate for acid soils, locally available liming materials, biological nitrogen fixation (see below), agroforestry systems, and other nutrient sources with low production and transportation costs. The use of rock phosphate is especially promising since low P availability is a primary constraint in weathered soils characteristic of many poor countries, and sources of rock phosphate are found in many developing nations (Smyth and Sanchez 1982; Gichuru and Sanchez 1988). These are promising solutions for farmers with some access to credit, transportation, and markets, as in many developing regions of Latin America and Asia. In subsistence agriculture characteristic of the poorest and most food insecure regions of Africa, even these inputs may be out of reach. A larger problem is that many poor farmers do not own their land, and therefore lack incentives for investing in soil fertility improvements.

The second leg of ISFM is soil management to conserve and enhance soil fertility, including erosion control, maintenance of soil organic matter (Fernandes et al. 1997), and enhancing nutrient bioavailability by promoting beneficial root symbionts, most notably via biological nitrogen fixation (Hubbell 1995) and mycorrhizal associations (Plenchette et al. 2005). Although the critical importance of these management tools has been known for decades, other than nitrogen fixing food legumes they are rarely used in the poorest countries. Indeed, many poor farmers use soil resources abusively, without apparent regard for the longer-term consequences of practices such as deforestation, residue burning, cultivation of steep slopes without runoff barriers. In some cases this is due to ignorance, compounded by disruption of traditional cropping practices by war, disease, and migration. Soil resources may be devalued because of the transitory nature of the cropping system, such as in the 'slash and burn' agriculture at retreating forest margins, or because the land is not owned by the farmer. In other cases soil fertility may be recognized as a resource but valued less than competing imperatives such as labor requirements for fuel wood collection, or the need to maximize food production in the short term. Many of the poorest farmers have little access to technical information or government services, and lack the exogenous incentives for soil conservation as a public good enjoyed by farmers in rich countries. The capability of this leg of ISFM to address the soil fertility crisis in the third world is therefore problematic, because of poor diffusion and adoption.

The third component of ISFM is the cultivation of crop species, genotypes and cropping systems that make optimal use of soil resources for food production while conserving soil fertility. Although crop species and cropping systems vary substantially in their ability to produce food in marginal soils, the adoption of new crop species and cropping systems is subject to some of the same socio-economic barriers noted above for soil conservation practices, with the added obstacle of cultural attachments to specific foods. For subsistence farmers, the crops they grow and consume are a dominant feature of their daily life. Strong preferences may exist for specific grain types within a crop species, regardless of yield advantages to introduced types. The cultivation of more nutrient- efficient crop species and cropping systems will probably be an important element of the adaptation of third world agriculture to global climate change, but these changes will likely be slow and difficult adjustments for traditional agricultural communities, made as a last resort. The prospect of cultivating new genotypes of existing crops with greater productivity in infertile soils is considerably more promising, especially if such genotypes have agronomic and grain characteristics that are similar to traditional landraces. Substantial genotypic variation exists in crop species for tolerance to Al toxicity (Kochian et al. 2004), Mn toxicity (Gonzalez and Lynch 1999) and low P (Lynch and Brown 2001), and this variation has been deployed through crop breeding programs in Africa, Asia, and Latin America (Lynch 2007). Selection for root traits that increase the acquisition of limiting nutrients such as phosphorus in crop plants (Fig. 4) is an increasingly important objective of breeding programs in developing countries (Yan et al. 1995). Successful genotypes can be adopted and disseminated through informal seed exchange networks, requiring no new additional information, credit, or social resources. Indeed, genotypes with greater productivity at suboptimal soil fertility are 'scale neutral' in that they would benefit producers at all resource levels improving yield with low inputs and reducing input costs in intensive systems.

There is a significant effort in the scientific community to biofortify crops

Fig. 4 Root traits of importance in adaptation to phosphorus deficiency include shallower root architecture, aerenchyma formation, longer and denser root hairs, greater root exudate and phosphatase production and mycorrhizal associations (Lynch 2007).



with trace elements to alleviate micronutrient malnutrition (Tanumihardjo et al 2008). Promising biofortification solutions include micronutrient enrichment of fertilizers (Cakmak 2009), intercropping of dicot and gramineous species (Zuo and Zhang 2009) and using molecular breeding and biotechnology to produce genotypes with root traits that increase the acquisition of limiting micronutrients (Zhu et al. 2007; Mayer et al. 2008). Based on known climate impacts on nutrient acquisition by crops (reviewed in this paper), projected climate changes in the 21st century are very likely to have net negative effects on trace element acquisition of crops in developing countries. Biofortification is a potentially powerful tool in offsetting edaphic and climate constraints to trace element acquisition by crops. However, to be successful, scientists will need to understand how climate conditions impact biofortification strategies.

Adoption of more nutrient-extractive genotypes without additional interventions may lead to accelerated nutrient mining in some systems (Henry et al. 2009). In upland systems where soil erosion causes major losses of soil fertility, greater crop biomass through increased nutrient extraction may actually enhance the sustainability of the system by reducing topsoil loss (Lynch 1998). In many low-input systems, increased productivity might permit the farmer to climb out of the poverty trap of low inputs and low yields, subject to the accessibility of additional fertility inputs as discussed above. Improved genotypes may represent the leading edge of technical intervention in low input systems, because of the relatively few barriers to their adoption, as well as the large impact they can have on crop yields. Genotypes selected for synergies with other fertility enhancing technologies, such as legume genotypes with superior utilization of rock P, leading to greater biological nitrogen fixation, or genotypes with greater soil cover that reduced soil erosion, may represent the leading edge of technology packages that could substantially improve and sustain the productivity of marginal lands.

Presently, the poorest nations confront a critical lack of trained people to implement this vision. Agricultural training has actually been de-emphasized in recent decades by development agencies and donors, and what training has occurred has often been directed to trendy fields such as biotechnology that have limited utility in the poorest countries. There has been inadequate attention to the complexity of these problems, including agro-ecological as well as socio-cultural factors, in favor of searches for technical solutions of limited scope, perhaps informed by the dramatic success and technical simplicity of the first green revolution. Thus despite the renewed emphasis on global food security by research donors, especially for Africa, it is not clear that sufficient progress will be achieved to avert a human disaster of epic proportions, as food insecure people are further marginalized by climatic shifts and the social disruptions that are likely to accompany them.

Conclusions

Although the interactions of global climate change and crop nutrition are not well understood, it is probable that the net effects of these changes will be negative for agricultural production in poor nations. Drought induced by higher temperatures and altered rainfall distribution would reduce nutrient acquisition, biological nitrogen fixation, and may disrupt nutrient cycling. More intense precipitation events would reduce crop nutrition by causing short-term root hypoxia, and in the long term by accelerating soil erosion. Increased temperature will reduce soil fertility by increasing soil organic matter decomposition, and may have profound effects on crop nutrition by altering plant phenology. Since soil fertility is already a primary constraint to food security in many developing regions, and crop production is already marginal, these stresses may be disastrous for vulnerable populations. Social adaptation to changing conditions is possible, although most of the technical options face serious obstacles of diffusion and adoption. An urgent effort is required to improve crop nutrition and soil fertility management in poor nations, integrating agro-ecological and socio-cultural aspects of the problem, to avert worsening of a situation that is already desperate.

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Implications of soil fertility to meet future demand: The Indian scenario

Annangi Subba-Rao • Kotha Sammi Reddy

Abstract India would need to produce 350 Mt of food-grains to feed the population of 1.41 billion by 2025. Contrary to ever increasing demand for food, the countrywide on-going long-term experiments revealed that the rate of response to added fertilizers and the factor productivity of major crops are declining year after year under intensive cropping systems due to various soil fertility problems such as (i) Wide nutrient gap between nutrient demand by crops and supply from soil and fertilizer, (ii) High nutrient turn over in soil-plant system coupled with low and imbalanced fertilizer use, (iii) Emerging deficiencies of secondary and micronutrients, (iv) Poor nutrient use efficiency, (v) Soil organic matter depletion and loss of soil fauna and flora, (vi) Insufficient input of organic sources because of other competitive uses, (vii) Acidification and aluminum toxicity in acid soils (viii) Soil erosion etc. This highlights the urgency for developing efficient nutrient management strategies for sustaining higher crop productivity and meeting future demands. Keeping this in view, lot of research effort is being made to develop efficient nutrient management strategies for producing higher yields and sustaining soil fertility. Integrated nutrient management strategies, balanced fertilization with NPK and other deficient nutrients in different crops, and soil test based fertilizer recommendations, were found to be efficient in improving the crop yield and to protect the soil fertility for future purposes. Involving legumes in cereal based cropping systems and the Real Time N Management using Leaf Colour Charts (LCC) in rice-wheat based cropping systems helped in improving the N use efficiency. Phosphorus and sulphur management strategies should include mobilization and efficient use of residual (accumulated) P or S in the soils. If the nutrients are applied on the basis of their availability in the soil, and by considering the cropping system as a whole rather than a single crop, the costly fertilizers can be saved. Split application of K, recycling of crop residues, the mobilization of K from different indigenous minerals such as waste mica, glauconite are emerging strategies of K management in different cropping systems. Since, different areas differ in their micronutrients status and extent of deficiency, the appropriate combination of nutrients for

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balanced fertilization will depend on the nature of soil and its nutrient status, and cropping systems followed in a given location. Therefore, it is necessary to develop situation-specific or area-specific customized fertilizer recommendations through NPK with required micronutrients.

Keywords Partial factor productivity • soil fertility issues • nutrient management strategies

Introduction

The current world population of 6 billion is expected to reach 8 billion by the year 2025. It is expected that most of the increase in population would occur in developing countries where nearly 1 billion people may suffer from chronic malnutrition. The Indian population, which increased from 683 million in 1981 to 1100 million in 2006, is estimated to reach 1412 million in 2025. To feed the projected population of 1.41 billion by 2025 India need to produce 350 million tonnes of food-grains (Subba-Rao and Sammi-Reddy 2008). The expanding food needs of future must be met through intensive agriculture without much expansion in the arable land and limited natural resources. The per capita arable land decreased from 0.34 ha in 1950-51 to 0.15 ha in 2000-01 and is expected to shrink to 0.08 ha in 2025. The current food grains production of 231 Mt (2007-08) is produced from the net arable land of 141 m ha. Contrary to this ever increase demand for food, the countrywide on-going long-term experiments revealed that the rate of response of crops to added fertilizers and the factor productivity of major crops are declining year after year under intensive cropping systems.

Declining crop response to fertilizer application

The partial factor productivity of fertilizers is declining in intensive cropping systems (Fig. 1). The incremental fertilizer use efficiency computed from 5-year average foodgrain production and fertilizer consumption decreased from 14 kg grain kg^{-1} NPK in 1974-75 to 6 kg grain kg^{-1} NPK in 2007-08 (Fig. 2). In urgency for higher production, no serious attention was given to the long-term soil fertility, and sustained high productivity. As a consequence, the annual compound growth rate of major crops has declined from 1980s to 2000s. Such gloomy trend was also registered in case of pulses and oilseeds, while cotton exhibited even negative growth rate. Rice productivity increased at an annual compound growth rate of 3.19 in 80s, which fell to 1.34 and 1.27 per cent in 90s and 2001-05, respectively. Wheat productivity decreased from 3.1 in 80s to 1.83 per cent in 90s (Table 1). Similar trends were also observed in case of oilseeds and pulses.

The decline in partial factor productivity and the growth rate of productivity of major crops as well as rate of response of crops to added fertilizer under

Fig. 1 Partial factor productivity of fertilizer NPK (PFPf) for foodgrain production in India (Source: Aulakh and Benbi 2008)

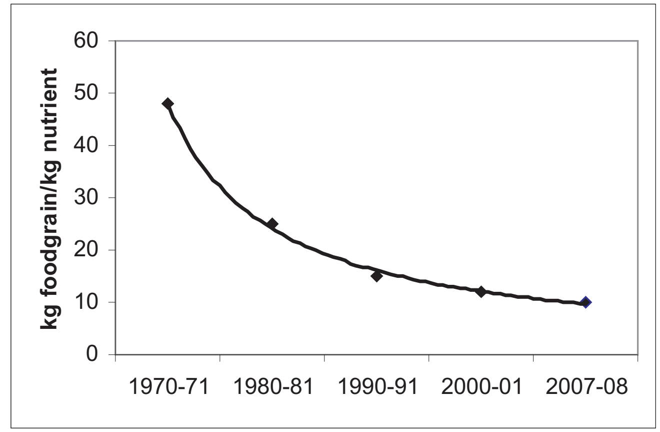
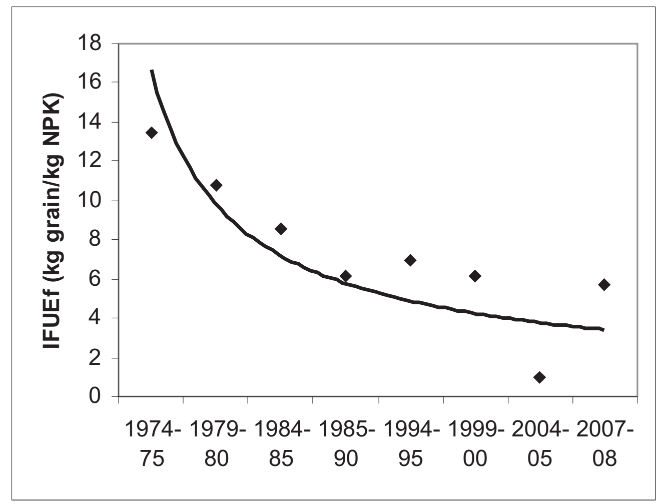


Fig. 2 Incremental fertilizer use efficiency over a period of time in India (Based on data from FAI 2008)



intensive cropping systems have possibly resulted from deterioration in overall soil fertility. The emerging issues of soil fertility are; wide nutrient gap between nutrient demand by crops and supply from soil and fertilizer sources; high nutrient turn over in soil-plant system coupled with low and imbalanced fertilizer use; emerging deficiencies of secondary and micronutrients; poor nutrient use

Table 1 Compound growth rates of productivity of foodgrains

Crop	Productivity (% per annum)		
	1980 - 1990	1991 - 2000	2001 - 2005
Rice	3.19	1.34	1.27
Wheat	3.10	1.83	-0.11
Pulses	1.61	0.93	2.79
Foodgrains	2.74	1.52	1.20
All major crops	2.56	1.33	1.96

Source: Government of India (GOI) Agricultural Statistics at a Glance (2004-05)

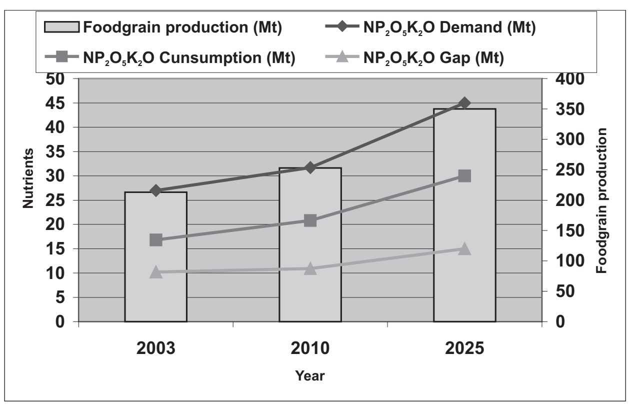
efficiency; soil organic matter depletion and loss of soil fauna and flora; insufficient input of organic sources because of other competitive uses; acidification and aluminum toxicity in acid soils; soil erosion.

Emerging issues of soil fertility

Wide nutrient gap between nutrient demand and supply

The growth in fertilizer consumption slowed down during 1990's and there was stagnation like situation for 4-5 years. Recently, there is again spurt in fertilizer consumption. After achieving a record consumption level of 18.1 Mt of NPK in 1999-00, the total NPK consumption hovered around 16-17 Mt during 2001-04 reaching 21 million tonnes in 2006-07. At present level of crops production, there exists a negative balance of 10 Mt between the nutrient (NPK) removal by crops and addition through fertilizers annually (Fig. 3).

Fig. 3 Projected food grain production in relation to nutrient (N-P_2O_5-K_2O) consumption, removal and gap (Source: Subba-Rao and Sammi-Reddy 2008).



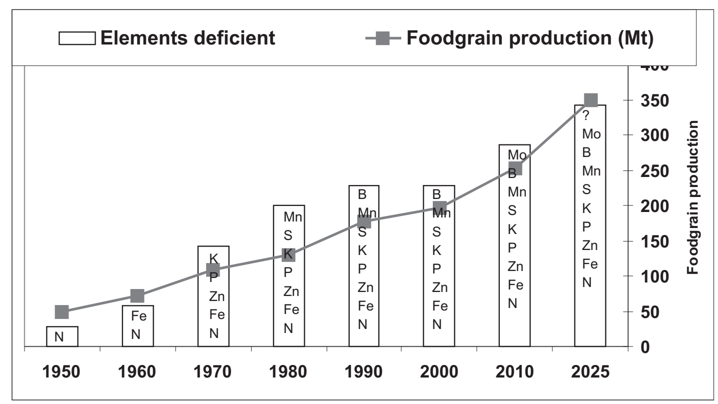
High nutrient turnover in soil-plant system coupled with low and imbalanced fertilizer use

The fertilizer consumption in India is grossly imbalanced since beginning. It is tilted more towards N followed by P. The decontrol of the phosphatic and potassic fertilizers resulted in more than doubling the prices of phosphatic and potassic fertilizers. Thus, the fertilizer consumption ratio is highly imbalanced ($N:P_2O_5:K_2O$, 5.5:2.1:1) during 2007-08 as against favorable ratio of 4:2:1 implying thereby that farmers started adding more nitrogen and proportionately less phosphatic and potassic fertilizers (FAI 2008).

Emerging deficiencies of secondary and micronutrients in soils

Intensive cropping systems are heavy feeders of nutrients and are bound to extract heavily the nutrient resources from the soil. Hence nutrient deficiencies are inevitable unless steps are taken to restore fertility levels through supplementation from external sources. Deficiencies of essential elements in Indian soils and crops started emerging since 1950s' and as food production increased with time the number of elements becoming deficient in soils and crops also increased (Fig. 4). Micro nutrient deficiencies in soils are also emerging as yield limiting factors. Analysis of more than 0.25 million soil samples revealed wide spread deficiency of Zn (49%) followed by S (41%), Fe (12%), Cu (3%), Mn (4%) and B (32%).

Fig. 4 Emerging deficiencies of plant nutrients in relation to increased foodgrain production (Source: Sammi-Reddy et al. 2007).



Poor nutrient use efficiency

The inputs in crop production mainly include nutrient supply (from soil, fertilizer and manure sources), irrigation, energy, plant protection measures and crop land.

The current status of nutrient use efficiency is quite low in case of P, N, Zn, Fe and Cu (Table 2). The use efficiency in case of micronutrients is extremely low (1 to 5).

Table 2 Nutrient use efficiency in India

Nutrient	Efficiency (%)
Nitrogen	30-50
Phosphorus	15-20
Potassium	70-80
Zinc	2-5
Iron	1-2
Copper	1-2

Source: Sammi-Reddy et al. 2007)

Declining organic matter status

Soil organic matter plays key role in soil fertility sustenance. In soybean-wheat system, without balanced input of nutrients, organic matter status of soil declined over a time in Alfisols of Ranchi. Whereas, balanced fertilization with NPK and NPK+FYM improved the organic matter status in Vertisols under soybean-wheat system at Jabalpur (Fig. 5). Thus, assessing soil organic carbon (SOC) accretions/sequestration under intensive cropping systems with different management practices plays an important role in long-term maintenance of soil fertility for meeting future demands.

Acidification and aluminum toxicity in acid soils

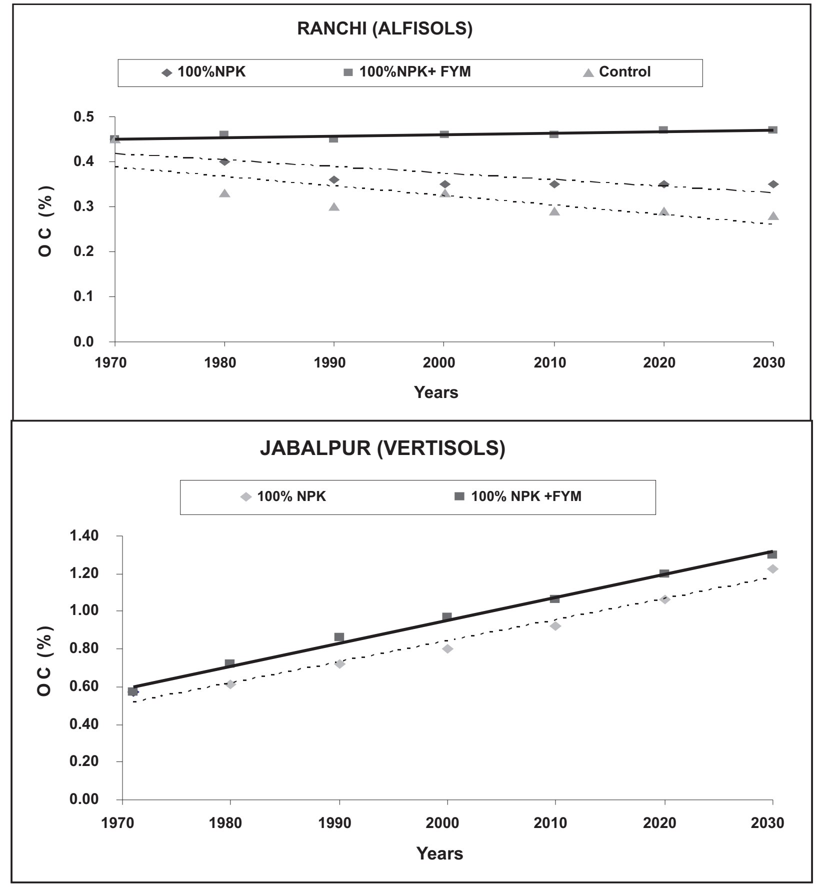
Nutrient imbalance is one of the main reasons for low productivity in acid soils. Solubility of Al, Fe and Mn being high in acid environment, these elements are available quite in excess at times causing toxicity. Soil acidity causes shortage of Ca and Mg. Ordinarily, B should be available under acid conditions but porous nature of topsoil allows the soluble B to leach down in the profile beyond the reach of the plant roots (Mondal and Khan 1972). In light textured soils, Zn becomes deficient. At mildly acidic conditions availability of P increases but with further increase in acidity P reacts with active Fe and Al to form insoluble compounds (Panda 1998).

Emerging soil fertility management strategies for meeting future demands

Integrated nutrient management strategies

The basic concept underlying the principle of Integrated Nutrient Management (INM) is to maintain or adjust plant nutrient supply to achieve a given level of crop

Fig. 5 Long-term trend of soil organic carbon status in Alfisol (Ranchi) and Vertisol (Jabalpur) under soybean-wheat system



production by optimizing the benefits from all possible sources of plant nutrients. The basic objectives of INM are to reduce the inorganic fertilizer requirement, to restore organic matter in soil, to enhance nutrient use efficiency and to maintain soil quality in terms of physical, chemical and biological properties. Bulky organic manures may not be able to supply adequate amount of nutrients, nevertheless their role becomes important in meeting the above objectives. Long-term studies being carried out under AICARP (Hegde and Dwivedi 1992) have indicated that it is possible to substitute a part of fertilizer N needs of kharif crop by FYM without any adverse effect on the total productivity of the system in major cereal based cropping systems such as rice-rice, rice-wheat, maize-wheat sorghum-wheat, pearl millet-wheat, maize-wheat and rice-maize. Organic manures alone cannot supply sufficient P for optimum crop growth because of limited availability and low P concentration. The organic manures are known to decrease P adsorption/fixation and enhance P availability in P-fixing soils (Reddy et al. 1999a). Organic anions formed during the decomposition of organic inputs can compete with P for the same sorption sites and thereby increase P availability in soil (Iyamuremye et al. 1996) and improve utilization by crops. Higher apparent P recovery by soybean-wheat system on Vertisol with a combination of fertilizer P

Table 3 IPNS strategies for major cropping systems.

Cropping system	IPNS strategy
Rice - wheat	Green manuring of rice with sunnhemp equivalent to 90 kg fertilizer N along with 40 kg N ha^{-1} produces yield equivalent to 120 kg N ha^{-1}.
	In an acid Alfisol soil, incorporation of lantana camera 10-15 days before transplanting of rice helps to increase the N use efficiency.
	Apply 75% NPK + 25% NPK through green manure or FYM at 6 t ha^{-1} to rice and 75% NPK to wheat.
	Inoculation of BGA @ 10kg ha^{-1} provides about 20-30 kg N ha^{-1}.
Rice - rice	Use of organic sources, such as FYM, compost, green manure, azolla etc. meet 25-50% of N needs in kharif rice and can help curtailing NPK fertilizers needs by 25-50%.
	Apply 75% NPK + 25% NPK through green manure or FYM at 6 t ha^{-1} to kharif rice and 75% NPK to rabi rice.
	A successful inoculation of blue green algae @ 10 kg ha^{-1} provides about 20-30 kg N ha^{-1}.
Rice-potato-groundnut	Use 75% NPK with 10 t FYM ha^{-1} in rice and potato.
Sugarcane based cropping systems	Combined use of 10 t FYM ha^{-1} and recommended NPK increases the cane productivity by 8-12 t ha^{-1} over chemical fertilizer alone.
Maize based cropping systems	Apply 50% recommended NPK as fertilizer and 50% of N as FYM in maize and 100% of recommended NPK as fertilizer in wheat.
Soybean -wheat	To get 2 t soybean and 3.5 t wheat, apply 8 t FYM ha^{-1} to soybean and 60 kg N+11 kg P ha^{-1} to wheat or apply 4 t FYM + 10 kg N+ 11 kg P ha^{-1} to soybean and 90 kg N+22 kg P ha^{-1} to wheat.
Pulses	Integrated use of FYM at 2.5 t ha^{-1} and 50% recommended NPK fertilizers plus rhizobium inoculation helps in saving of 50% chemical fertilizers.
Sorghum based cropping system	Substitute 60 kg N through FYM or green Leuceana leaucocephala loppings to get higher yields and FUE.
Cotton	50% of recommended NPK can be replaced by 5 t FYM ha^{-1}.
Oil seeds (Mustard, Sunflower etc.)	Substitute 25-50% of chemical fertilizer through 10 t FYM ha^{-1} to get higher yield and FUE.

(Source: Subba-Rao et al. 1995; Mondal and Chettri 1998; Acharya et al. 2003)

and manure was observed (Reddy et al. 1999b). Therefore, it is necessary to popularize the IPNS strategies for different cropping systems for achieving higher crop yields and fertilizer use efficiency. The INM strategies developed for major cropping systems all over the country are compiled in the Table 3.

Integrated use of farmyard manure and inorganic fertilizer nitrogen not only produced higher sustainable yield index SYI of Rice-black-horsegram system (Table 4) but also maintained the highest soil quality index under dry land conditions (Sharma et al. 2005).

Table 4 Relative soil quality index (RSQI) and SYI under rainfed rice-blackgram-horsegram system after 7 years of cropping at Phulbani, Orissa

Treatment	SYI*	RSQI**
Control	0.13	-
RDF (inorganic)(R-60-30-30 & BG - 20-40-40)	0.32	0.79
25 kg N (FYM)	0.31	0.55
15 kg N FYM + 20 kg N (inorg)	0.45	1.00
15 kg N GLM + 20 kg N (inorg)	0.39	0.66
15 kg N FYM + 15 kg N GLM	0.27	0.70

*SYI- Sustainable yield index; **RSQI- Relative Soil Quality Index, RDF:Recommended dose of Fertilizer, FYM:Farmyard Manure, GLM:Greenleaf Manure
Source: Sharma et al. (2005)

Future prospects of integrated nutrient management in India

Potential availability of organic resources

It is estimated that 300, 375 and 16.5 million tonnes of crop residues, livestock dung and human excreta per annum, respectively are available in the country (Tandon 1996). Of this, around one third of crop residues and half of the livestock dung and 80% of human excreta are available for use in agriculture. The greater use of these materials in agriculture can ensure better soil fertility and sustained high productivity. The availability of these organic sources is likely to increase in future. It is estimated that for every million tonne increase in food grain production, there will be production of 1.2-1.5 million tonnes of crop residue and every million increase in cattle population will provide additional 1.2 million tonnes of dry dung per annum. Thus the estimated NPK supply from all the wastes including crop residues is 5.0, 6.25 and 9.25 million tonnes, respectively during 1991, 2011 and 2025. A greater use of organic input has the potential to decrease the expected negative balance since greater availability of alternative fuel such as LPG in rural households in future may make the more organics available for use in agriculture.

If judiciously used, organic manures may help in meeting future food demand by narrowing down the nutrient gap. Several fertilizer prescription equations based on Soil Test Crop Response (STCR) have been developed for different crops grown on contrasting soils across the country for computing fertilizer doses under INM (Subba-Rao and Srivastava 2001). Nutrient availability coefficients of manures have been taken into account while developing these fertilizer prescription equations. The STCR based fertilizer and manure based recommendations should be popularized in place of general blanket rates of applications for greater balance in nutrient supply and efficient utilization of applied nutrients.

Prospects of organic solid waste recycling

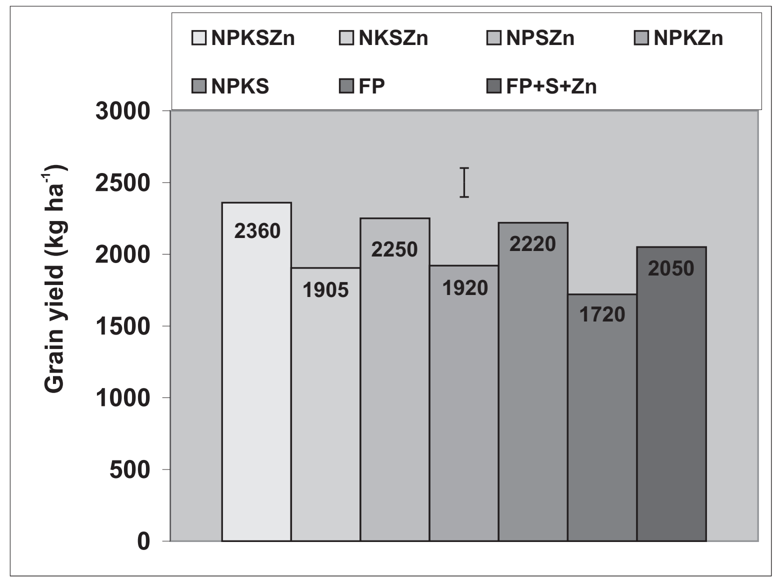
Organic solid wastes generated in large quantities by domestic, commercial and industrial activities are often indiscriminately disposed on the soils. It has been estimated that a large amount of urban compost is being generated every year from different cities of India which will reach to around 10.4 million tonnes per year during 2025 as a result of phenomenal increase in urban population and ever increasing industrialization (Sammi-Reddy et al. 2007). This could be increased to 20.8 million tonnes per year by 2025, if entire compostable material (42%) under goes composting. This, however, is possible by improving the composting technology of city wastes that is also cost effective. By following the proper composting techniques, the municipal solid wastes can provide an amount of 2.85 lakhs tonnes of N, P_2O_5 and K_2O that could be increased to about 5.4 lakh tonnes per year by 2025. The currency value of compost is currently 158.3 crores and can go up to 659.6 crores by the year 2025 through the involvement of improved technology in compost making.

Balanced fertilization through inorganic fertilizers

Even though sizeable quantity of cattle dung, crop residues, municipal solid wastes are available in India, they are not sufficient to cover the entire cultivated area in a particular year with integrated nutrient management. A survey conducted in Central India revealed that due to insufficient availability of manures, farmers are trying to cover entire land holding in 3-4 years with INM (Sammi-Reddy et al., 2005). With this approach, it is possible to cover the entire holding in 3-4 years frequency with the available FYM in case of small and marginal farmers (1-2 ha). But in case of medium and large farmers (6-10 ha), only 58% of their holding was covered with INM in 3-4 years. Even after 4 years, 42% of the holding may not receive organic manure in case of medium and large farms. Therefore, farmers should go for balanced fertilization with inorganic fertilizers for realizing the full potential of crop yield on portion of their holding.

In an era of multiple nutrient deficiencies a single nutrient approach can lower Fertilizer Use Efficiency. Balanced nutrition implies that there are no deficiencies, no excesses, no antagonisms and no negative interactions. All deficient nutrients must be at an optimum rate by themselves and in relation to each other enabling positive interactions to enhance yields. Field trials conducted in different villages of Central India on black soils deficient in N, P, S and Zn showed that the balanced fertilization through application of NPKSZn at recommended rates produced higher soybean seed yield by 30-35% over farmers' practice (FP) (12 kg N and 13 kg P ha^{-1}) (Fig. 6). Skipping of application of P and S had resulted in 15-19% yield reduction in soybean seed yield as compared to NPKSZn treatment. Similarly the soybean seed yield was reduced significantly when Zn was not applied. Application of S (20 kg ha^{-1}) and Zn (5 kg ha^{-1}) with the farmers' practice (FP+S+Zn) produced 19% more soybean yield over farmers' practice (Sammi-Reddy et al. 2007).

Fig 6 Effect of balanced fertilization on soybean seed yield (I indicates the l.s.d. at P = 0.05). (Source: Sammi-Reddy et al. 2007)



Soil test based fertilizer recommendations

General blanket fertilizer recommendations are static and can't commensurate with variability and changes in soil nutrient status, crop demand and crop management. The application of fertilizers based on recommendations emanating from Soil Test Crop Response Correlation (STCR) data may be the alternative approach. Among the various methods, the one based on yield targeting is unique in the sense that this method not only indicates soil-test based fertilizer dose but also gives the level of yield the farmer can hope to achieve if good agronomic practices are followed in raising the crop. The essential basic data required for formulating fertilizer recommendations for targeted yield are (i) nutrient requirement in kg/100 kg of produce (ii) the per cent contribution from the soil available nutrients, and (iii) the per cent contribution from the applied fertilizer nutrients (Ramamoorthy et al.1967). These parameters are calculated as follows (Subba-Rao and Srivastava 2001):

i) Nutrient requirement of N, P and K for grain production (NR)

$$NR\,(kg\ of\ nutrient\ /100\ kg\ of\ grain) = \frac{Total\ uptake\ of\ nutrient\ (kg)}{Grain\ yield\ (100\ kg)}$$

ii) Per cent contribution of nutrient from soil (%CS)

$$\%CS = \frac{Total\ uptake\ in\ control\ plot\ (kg\ ha^{-1})}{Soil\ test\ value\ of\ nutrient\ in\ control\ plot\ (kg\ ha^{-1})} \times 100$$

iii) Per cent contribution of nutrient from fertilizer (% CF)

$$Contribution\ from\ fertilizer\ in\ treated\ plots\ (CF) = Total\ uptake\ of\ nutrients - (Soil\ test\ values\ of\ nutrients\ in\ fertilizer\ treated\ plots \times CS)$$

$$\%CF = \frac{CF \times 100}{Fertilizer\ dose (kg\ ha^{-1})}$$

iv) Calculation of fertilizer dose (FD)
The above basic data are transformed into workable adjustment equation as follows:

$$FD = \left(\frac{NR}{\%CF} \times 100 \times T\right) - \left(\frac{\%CS}{\%CF} \times Soil\ test\ value\right)$$

$$FD = (a\ consant \times T) - (b\ consant \times soil\ test\ value\ in\ kg\ ha^{-1})$$

Where T is the yield target (q ha^{-1})(i.e. Quintal=100 kg)

Ramamoorthy et al. (1967) refined the procedure of fertilizer prescription initially given by Truog (1960) and later extended to different crops in different soils (Randhawa and Velayutham 1982). Targeted yield concept strikes a balance between 'fertilizing the crop' and 'fertilizing the soil'. The procedure provides a scientific basis for balanced fertilization and balance between applied nutrients and soil available nutrients. In the targeted yield approach, it is assumed that there

is a linear relationship between grain yield and nutrient uptake by the crop, and for obtaining a particular yield, a definite amount of nutrients is taken up by the plant. Once this requirement is known for a given yield level, the fertilizer needed can be estimated taking into consideration the contribution from soil available nutrients.

The advantage of application of fertilizer nutrients based on the target yield approach has been demonstrated (Srivastava et al. 2001). The soil test based fertilizer dose computed from the above equations produced significantly higher yields over the farmers' practice (FP) at all the sites (Table 5).

Table 5 Seed yield of soybean under farmers' practice (FP) and Soil test crop response (STCR) based fertilizer dose.

Site	Treatment	Fertilizer dose (kg ha^{-1})			Grain yield (kg ha^{-1})
		N	P_2O5	K_2O	
Site 1	FP	9	23	0	1080
	STCR (1680 kg ha^{-1})*	0	57	9	1650
Site 2	FP	32	23	0	2030
	STCR (1680 kg ha^{-1})	44	0	19	2260
Site 3	FP	34	12	0	1760
	STCR (2000 kg ha^{-1})	42	65	0	2270
Site 4	FP	45	82	12	1770
	STCR (2000 kg ha^{-1})	17	37	38	2170
Site 5	FP	80	100	36	1550
	STCR (2400 kg ha^{-1})	1	0	0	2390
Site 6	FP	23	80	29	2100
	STCR (2400 kg ha^{-1})	34	13	11	2310

*Figures in the parenthesis are target yield of soybean; FP - Farmers' practice; STCR - Soil test crop response based fertilizer dose

Under INM, fertilizer and manure prescription equations for different crops have been developed on the basis of soil test value, nutrient release coefficients of manures, and yield target. These STCR based prescription equations for computing fertilizer and manure doses to get a particular target yield of different crops have been placed on the Indian Institute of Soil Science website (www.iiss.nic.in). End users/farmers can easily compute manure and NPK rates of application to a particular crop, if he knows his soil test values and target yield.

Efficient use of applied nutrients in biological systems

Nitrogen management strategies

Soil fertility maps prepared by Motsara (2002) showed that the N is universally deficient in Indian soils and continued to be deficient. The N use efficiency is very low which hovers around 50% and may even less in rice (40%). Therefore, N management is very important in future for meeting the expected demands.

Choice of suitable crops and cropping systems, plays an important role in N management. Growing legumes in cropping systems, not only help in meeting part of the heavy nitrogen needs of modern intensive cereal-cereal cropping systems such as rice-rice, rice-wheat, maize-wheat etc. but also maintain soil organic carbon (SOC) in the long run. It has been observed that the content of SOC in rice-wheat-green gram crop sequence was higher than rice-wheat-fodder followed by rice-mustard-green gram and rice-mustard-fodder sequences possibly due to inclusion of legume in cereal-cereal crop rotation (Sharma and Bali 2000).

In semi-arid areas, continuous cropping reduces the decline in soil organic matter and microbial biomass compared with a wheat-fallow rotation (Campbell et al. 1991). Comparison of maize and sorghum cropping systems grown continuously and in rotation with soybean generally shows an increase in microbial biomass in the rotation (Table 6). Over a period of 5 years the net change in SOC was negative under cereal-cereal sequences, whereas in other sequences having legume component the changes were positive (Singh et al. 1996). Mixed or intercropping systems are also advantageous in many crops. For example, growing pea or pigeon pea with maize and green gram or black gram maintained higher organic carbon than growing maize with soybean (Sharma and Bali 2000).

Table 6 Effect of crop rotation on microbial biomass C and organic C

Previous crop	Soil type	Microbial biomass (mg C kg^{-1})			Organic C (g C kg^{-1})		
		Monoculture	Soybean	Difference (%)	Monoculture	Soybean	Difference (%)
Sorghum	SiCL	600	650	+8.3	14.8	14.9	+0.1
Corn	SiCL	108	128	+18.5	16.7	15.6	+6.6

The synchrony between crop demand and supply is important for efficient N use. In many field situations up to 50% of applied N is lost due to lack of synchrony. The plant need-based application of N is crucial for high yield and N use efficiency. The use of chlorophyll meter and leaf colour chart (LCC) have been found to reduce fertilizer N input and increase N use efficiency while minimizing the flow of excessive N to water bodies (Balasubramanian et al. 1999; Peng et al. 1996). Average recovery efficiency of applied N by farmers was 34% compared to 64% in SPAD- guided plots. Studies conducted in Punjab using chlorophyll meter showed that application of 90 to 105 kg N ha^{-1} in three split doses at 14, 35, and 50 days after transplanting resulted in better agronomic efficiency (Bijay-Singh et al. 2002) as compared to blanket application of 120 Kg N ha^{-1}. More N application at tillering and up to flowering stage is needed while reducing basal application at the beginning of crop growth (Yadvinder-Singh et al. 2007).

Since chlorophyll meter is an expensive device, simple and inexpensive alternative is to use LCC. Because the chlorophyll meter measures leaf color as a proxy for leaf N, a simplification for this is to use the green colour as an indicator of plant N status. Results show that use of LCC for the application of N fertilizer to rice can economise N dose (20-30 kg N ha^{-1}). While comparing various N management techniques for rice, Buresh et al. (2001) observed that the LCC method produced the highest total grain yield and fertilizer N use efficiency. Similar results have also been obtained in trials at farmers' fields at several locations in Pubjab (Yadvinder-Singh et al. 2007). Evaluation of LCC at farmers' fields for four years showed that it could result an economy of 26% fertilizer across sites and seasons. The results revealed that only a small basal dose of 20 kg N ha^{-1} at transplanting is desirable (Table 7). There is a need to popularize LCC among the farmers growing rice throughout the country.

Another strategy is to consider yield plateau models for computing nitrogen fertilizer doses to different crops to avoid the excess use of N fertilizers than the actual need. Alivelu et al. (2003) found that even though linear response plateau (LRP), quadratic response model with yield plateau specification (QRP) and modified Mischerlich's equation predicted nearly the same maximum yield, fertilizer recommendations estimated by LRP and QRP models were considerably lower than that given by modified Mischerlich's equation.

Table 7 Agronomic efficiency, recovery efficiency and partial factor productivity of applied fertilizer N in rice as influenced by N application method at on-farm locations in Punjab.

Year (No. of sites)	Method of N application	Agronomic efficiency (kg grain kg^{-1} N)	Recovery efficiency (%)	Partial factor productivity (kg grain kg^{-1} N)
2000(8)	RN	20.8	30.9	57.2
	LCC (-B)	27.4	42.7	82.7
	LCC (+B)	28.1	42.1	86.3
	LSD (0.05)	3.7	4.1	6.1
2001 (8)	RN	15.4	29.1	59.9
	LCC (-B)	19.8	38.9	97.5
	LCC (+B)	21.6	45.4	90.5
	LSD (0.05)	2.4	3.6	7.4
2002 (11)	RN	11.3	39.8	52.1
	LCC (-B)	19.2	58.3	91.7
	LCC (+B)	16.4	52.7	73.8
	LSD (0.05)	4.3	5.9	7.9

Rn = Recommended fertilizer management; LCC = Leaf color chart;
-B = No basal N applied at transplanting; =B = 20 kg N ha^{-1} applied as basal

Source: Yadvinder- Singh et al. 2007

The first systematic soil fertility map of Indian soils published in 1967 by Ramamoorthy and Bajaj (1969) showed around 4% samples high in available P. But the recently published soil fertility map (Motsara 2002) indicates around 20% of soils high in available P. This is probably due to continuous use of phosphatic fertilizers by the farmers. Therefore, if the farmers apply P as per the soil tests, there is a chance to save a lot of valuable phosphatic fertilizers. The future strategy of P management should aim at utilization of build-up P in soils testing high in available P. Several studies have been conducted to evaluate the response of crops to residual P (Subba-Rao and Ganeshamurthy 1994). The results revealed that application of 39 kg P ha^{-1} to soybean had significant effect on yields of 2 subsequent crops (wheat and soybean) whereas the same amount of P applied to wheat had significant effect on only one subsequent crop (soybean) in Vertisols (Subba-Rao et al. 1996). A residual P management technology has been developed in which the application of 39 kg P ha^{-1} either to soybean or wheat produced the statistically similar yield as the application of 26 kg P ha^{-1} to each crop, thus, saving of about 13 kg P ha^{-1} $year^{-1}$ (Sammi-Reddy et al. 2003).

The application of only maintenance dose of P, equivalent to amount of P removed by the previous crop has been suggested (Souza et al. 1987), under situations where available P status is higher than 14 mg P kg^{-1} soil. Similarly, a maintenance fertilization dose equivalent to P removal by crops, supplied either through 5 t FYM plus 8 kg fertilizer P ha^{-1} or 10 t FYM ha^{-1} to soybean and 10 kg fertilizer P ha^{-1} to wheat was good enough to obtain the target of 2 t soybean and 4 t wheat yields ha^{-1} and helped to maintain P fertility at near initial level (Reddy et al. 2006) (Table 8).

Management of acid soils should aim at realization of production potential either by addition of amendments or to manipulate agricultural practices to enhance fertilizer use efficiency. Application of lime as amendment to neutralize the exchangeable Al to a certain extent has been found effective. Liming improves the base status, inactivates Fe, Mn and Al in soil solution and thus reduces P fixation. But the farmers are reluctant to apply large quantities of liming materials for reclamation due to economic reasons. Rattan (2007) suggested ameliorating the acid soil with minimum quantities of lime with application of all other macro and micronutrients at recommended rates in a balanced way. Studies conducted in 7 states of India revealed that the application of lime @ 200 to 300 kg ha^{-1} improved the crop yields by 16-48%. Application of half of the recommended rate of NPK with lime was at par or superior to the full dose of NPK without lime (Sharma and Sarkar 2005). The strategies for enhancing P utilization efficiency in different cropping systems on acid soils are presented in Table 9.

Table 8 Soil test maintenance P requirement and its relationship with crop yield and P removal (uptake) under different P supply strategies.

P supply strategy (PSS)*	Soil test maintenance P requirement (STMPR) of soybean-wheat rotation (kg ha^{-1} yr^{-1})	Yield levels of l rotationa crops at STMPR (Mg ha^{-1})		Total annual P removal at STMPR (kg ha^{-1} yr^{-1})	STMPR to P removal ratio
		Soybean	Wheat		
PSS-I	36.1 (22.2 + 13.9)[@]	1.91	4.10	25.2	1.4
PSS-II	26.3 (16.2 + 10.1)	1.86	4.06	23.4	1.1
PSS-III	24.1 (14.8 + 9.3)	1.90	4.01	23.7	1.0

* PSS-I, PSS-II and PSS-III imply P supply through inorganic (fertilizer), organic (FYM) and integrated (fertilizer+FYM) sources, respectively to soybean. P supply to wheat was solely through fertilizer under all strategies.

@ Figures in parentheses indicate the P rates for component crops of annual soybean-wheat rotation obtained by splitting STMPR in the same ratio of 1.6:1 as was used in the treatments for soybean and wheat.

Table 9 Strategies for enhancing P use efficiency in crops in acid soils.

Cropping System	Agro-climatic zone	Strategy
Maize-wheat	Western Himalayan region (pH <6.0)	Apply 60 kg P205 ha^{-1} as a mixture of SSP and rock phosphate in a ratio of 1:2 to maize. However, apply SSP to following wheat for higher FUE.
Rice-rice	Eastern Himalayan region (pH<5.1)	Apply 30 kg P_2O_5 ha^{-1} to summer as well as monsoon rice in the form of rock phosphate or a mixture of SSP and RP in 1:1 ratio.
Rice-rice	Brahmaputra Valley	Apply MRP at 40 kg P_2O_5 ha^{-1} at 20 day before rice transplanting.
Rice-rice	Lower Gangetic Plain region	Use SSP and rock phosphate in 1:2 ratio as basal dressing for higher P use efficiency.
Rice-rice	Central Plateau & Hills region	Recommended P dose is 60 kg P_2O_5 ha^{-1} as rock phosphate.
Pulses	Southern plateau & Hills region	Rhizobium inoculated seed should be treated with 1.5 kg of finely powdered lime (300 mesh). Liming rate should be determined by soil test method and the rate should be that it can only upset the Al toxicity and does not impair the K and Ca balance.
Rice-rice	East & West Coast Plains & Hills region	Apply 60 kg P_2O_5 ha^{-1} as rock phosphate 3 weeks before transplanting.

Source: Subba-Rao et al. 2004

At present level of crop production, there exists a negative balance of 10 Mt between the nutrient (NPK) removal by crops and addition through fertilizers, annually (Fig. 3). Of the current negative NPK balance of 10 Mt, 6.9 Mt is K, 1.9 Mt N and 1.2 Mt P. Annual fertilizer potassium consumption is only 2.6 Mt against the crop removal of 9.5 Mt of K from Indian soils. Farmers are not applying sufficient levels of K as crop yields are not suffering due to the reason that most of the Indian soils are considered as rich in K. However, If this trend continues for a longer time, many of the soils may be depleted of K reserves. Continued mining of K from soil through crop uptake may bring certain changes in the forms and mineralogy of K in soils. Continuous rice-wheat cropping system for 8 years in Vertisols, with only N application, resulted in an increase in the negative K balance from 50 kg ha^{-1} $year^{-1}$ in control to 102 kg ha^{-1} $year^{-1}$ at 90 kg N ha^{-1}.

Entire fertilizer K requirement in India is being met through imports, therefore, K management strategies should be developed to utilize indigenous sources of K such as crop residues, K rich minerals etc for meeting at least partly requirement. About 336 million tones of crop residues are produced in a year at the current level of crop production which can supply 5.04 Mt K (Srinivasa-Rao et al. 1996). But most of the mechanical harvest-borne crop residues are being burnt by the farmers in rice and wheat growing areas. Burning the residues causes loss of precious organic matter, plant nutrients and environmental pollution. Several strategies have been developed to recycle mechanical harvest-borne rice and wheat straws without adversely affecting crop yields. Recycling of crop residues with green manures, organic manures, N fertilizers etc were found to be efficient strategies. Experiments conducted in Punjab have shown that co-incorporation of green manure and crop residues of wheat and rice helped alleviate the adverse effects of unburnt crop residues on crop yields**.** Therefore, the technologies developed for the incorporation of mechanical harvest-borne crop residues need to be popularized among the farmers in the rice-wheat and rice-rice growing areas.

A number of recent studies have indicated that incorporation of rice or wheat residues in rice-wheat cropping system can built up soil fertility and improve soil physical properties**.** Studies conducted at Bhopal showed that mechanical harvest borne wheat residue incorporation/surface retention with on-farm FYM resulted in higher crop yields in soybean-wheat cropping system and led to an improvement in organic C and nutrient availability of soil under soybean-wheat system as compared to residue burning (Table 10).

India has the world's largest deposits of micas, which contain about 8-10% K_2O readily available as mine wastes as well as poor grade ores which find little use. Muscovite mica is widely mined and used as an electrical insulator. Of the

Table 10 Effect of wheat residue management options and N sources on soybean seed yield (kg ha^{-1})

N sources	Wheat residue management options for soybean		
	Burning	Soil incorporation	Surface retention
Control	402	440	459
Fertilizer -N	525	608	600
FYM	611	696	690
PM	588	656	678
GLM	505	567	579
l.s.d (P=0.05)	RMO - 23.3	N source - 27.5	RMOxN source -NS

Source: Reddy 2007

total quantity mined, about 75% is wasted during dressing of the blocks. Biotite mica is rarely used for any commercial purpose but very large reserves are available (Varadachary 1992). Enriched compost using rice-straw, dung, rock-phosphate and waste mica, increase in the release of water soluble P and K (Nishanth and Biswas 2008). Vast reserves to the tune of 938 Mt of glauconite sand stones are available in India. It contains 5.4% K_2O. Mazumdar et al. (1993) perfected a technique to increase the water soluble K by partial acidulation of the concentrated glauconite (with sulphuric acid as medium and fluorite mineral as additive) to produce acidulated material to be used as mineral fertilizer.

Potassium fertilizers are generally broadcast or spread on the surface and mixed with surface soil. Only in soils with a low level of available K or with a high K fixing capacity, band placement is recommended. In some soil-crop situations, split application is emerging as an alternative to basal application. The situations are (i) rice grown in light textured soils and acid soils in high rainfall areas in order to reduce leaching losses; (ii) low tillering and late maturing varieties, where the natural supply of K from soil plus irrigation which decreases in the later stages of crop growth (iii) in highly reduced soils where conditions may hinder K uptake; and (iv) during the monsoon season. Several studies have indicated the beneficial effect of application of K in 2-3 splits in rice. Split application of both N and K in rice is recommended in Andhra Pradesh, Kerala, Orissa and Uttar Pradesh. Split application of K is also recommended in crops like sugarcane, banana, grape-vines, papaya, pineapple and tea in different states (Tandon and Sekhon 1988). Most of the red and laterite soils of the country are deficient in available K. Recently conducted experiments (Wanjari 2009) revealed that split application of recommended rate of K (50% K at basal and 50% K at 30 days after sowing) with 100% NP produced significantly higher finger millet yield over 100% NP with recommended rate of K as basal application. Crops like potato, tapioca, tea, rubber, coconut, tobacco, banana, leafy vegetables like cauliflower and cabbage, forage crops like alfalfa are the heavy feeders of K. Therefore, it is necessary to apply higher doses of K in the areas growing these crops as compared to other crops.

Sulphur management strategy

Several factors lead to decline in S status of soil over a period of time. Plant-available S is derived primarily from the decomposition of plant residues and soil organic matter. Sulphur deficiency is most common in soils, which are inherently low in S, sandy texture, low in organic matter and soils prone to high leaching. Historically when ordinary superphosphate which contains 12% S was in common usage, S was inadvertently applied to many soils.

The soils testing below 10 mg S kg^{-1} soil have been considered to be S deficient. Fertilizer S application rates to different crops should be based on the available S status of the soils. Depending upon the soil test value of S, the optimum rate of application of S to oilseed crops varied from 15 to 60 kg S ha^{-1} (Table 11) (Singh 1999). Since the S requirement of crops is more at early growth stages, its application may preferably be made prior to sowing or bud initiation or flowering under moist conditions to ensure high availability for better crop yields. Like P, continuous application of S fertilizers to different crop rotations leads to build-up of soil S status. Therefore, it is essential to utilize the residual S left over in the soils during next crop for higher efficiency. Singh and Saha (1997) found that application of 20 kg S ha^{-1} to both soybean and wheat or application of 40 kg S ha^{-1} to either soybean or wheat was found adequate to sulphur requirement of a soybean – wheat rotation. Ganeshamurthy and Takkar (1997) found that the S applied @ 60 kg ha^{-1} to soybean showed residual effects in two succeeding crops (wheat and soybean) while the same applied to wheat showed residual effect in only one succeeding crop (soybean). Sulphur applied to soybean was more efficiently utilized by succeeding crops as compared to that applied to wheat in the system.

Table 11 Fertilizer S recommendations based on available S status of soils

Available S (mg kg^{-1}) in soil	S fertility class	Amount of S to be applied (kg ha^{-1})
<5	Very low	60
6-10	Low	45
11-15	Medium	30
16-20	High	15
>20	Very High	0

Source: Singh 1999

Micronutrient management strategies

Red and black soils of Deccan Plateau, black soils of Central India, Bundelkhand region and Eastern Ghats, Red loam soils of Tamil Nadu, Alluvial soils of Eastern India and North-East India are deficient in Zn to the extent of 50-74% (Singh 2009). Deficiency of B is most widespread in course textured sandy soil, red and laterite soils and acid soils of Deccan Plateau, Eastern Plateau, Assam and Bangal Plains and Northeastern Hill Region. In alluvial soils of Indo-Gangetic Plains, iron deficiency is most common in rice and Mn deficiency is most common in wheat under rice-wheat system. The appropriate combination of nutrients for balanced fertilization will depend on the nature of soil and its nutrient status, and cropping systems followed in a given location. Therefore, it is necessary to develop situation-specific or area-specific customized fertilizer recommendations through NPK with required micronutrients. Tandon and Narayan (1990) identified components of balanced fertilization for different situations (Table 12). If the estimated level of pulse production has to be achieved more phosphate has to be made available to the pulse growing farmers at an affordable price keeping in view the fact that the risk factor under dry land conditions is much higher.

Table 12 Components of balanced fertilization under different situations

Situation	Component of balanced fertilization (Nutrients whose application needed)
Red and lateritic soils	N, P, K with lime
Newly reclaimed alkali soils	N & Zn
Many areas in alluvial soils, wheat belt	N, P, K, Zn & S / N, P, Zn & S / N, P & Zn / N, P, K, & Zn
Many areas under oil seeds	N, P, K, & S / N, P, & S / N, P, Zn & S / N, P, S & B
Legumes in oilseeds	N, P, K, Ca & Mo
Malnad area of Karnataka	N, P, K, Mg, S and Zn
High yielding tea plantation	N, P, K, Mg, S & Zn

Source: Tandon and Narayan 1990

Improved agronomic practices

Globalization and urbanization has changed the paradigm for agriculture. The age old paradigm based on massive soil inversion with a plough has changed to a new paradigm of conservation agriculture (CA) wherein some observed major shifts includes conventionally tilled wheat to Zero tillage/reduced tilled wheat, puddled transplanted rice to direct dry seeded rice (zero-till rice), residue burning/residue incorporation to residue retention (mulching), monocultures to diversified agriculture and sole crops to Intercrops in bed-planting.

The new multi-crop planters enable the farmers to plant the crops timely in residual soil moisture of preceding crops to save pre-sowing irrigation water, diesel, and labour. The drill places seed and fertilizers at an appropriate soil depth in a narrow slit which helps in enhancing the fertilizer use efficiency. By end of rabi 2006-07 more than 3.13 Mha were planted to zero-till, and reduced till systems in Indo-Gangetic Plains (Gupta 2006). The CA production technology package is emerging as a clear winner. Probably it is adaptable, divisible, reliable, and spreading faster than projected.

Conclusions

After green revolution, food grain production in India increased from 74 Mt in 1966-67 to 231 Mt in 2007-08 with corresponding increase in the fertilizer consumption from 1.1 Mt to 22 Mt. But growth in fertilizer consumption was mainly in N and P to very little extent in K. Therefore, the continuous application of only N and P that too in lower rates than recommended led to emergence of secondary (S) and micronutrient (Zn, B, Fe, Mn, etc) deficiencies in soils. As a result, the rate of response of crops to applied fertilizers, factor productivity of crops, and nutrient use efficiencies declined year after year. Nutrient management strategies such as Integrated Nutrient Management, Balanced fertilization through inorganic fertilizers, Soil test based fertilizer recommendations, Recycling of crop residues, Customized fertilization as per the situation, Efficient management of residual or accumulated nutrients in soils appear to be viable measures to meet the food grain demands.

The future research should aim at

- Precision agriculture is likely to play a greater role in which site-specific nutrient management has to be coupled with temporal specific nutrient needs of crop. Very little work has been done on this aspect.
- Nutrient management strategies need to be developed for mobilizing nutrients from indigenous and cheaper minerals and industrial by-products so that pressure on costly imported fertilizers can be reduced.
- Improved nutrient management technologies should be recommended and popularized among the farmers along with other pest, weed and water management options as a package of practices.
- Plant analysis, usually used for horticultural and vegetable crops, must be made more popular.
- The K balance of Punjab, Haryana and other Northern Indian states appears to be worst in the country as the K consumption is very meager. It remains to be seen that how long soil K reserves could sustain present level of crop productivity. Keeping in view the continuous depletion of K reserves by intensive cropping, a close watch is needed to monitor K deficiency assuming significance in crop production.

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Particular issues in plant production under acid soils: The Orissa scenario

N Panda

Abstracts Acid soils in Orissa are formed due to weathering caused by hot humid climate and heavy precipitation. Seventy percent of the cultivated land in the state is acidic that particularly occurred in the uplands. The common problems with respect of crop production are low pH, low CEC, nutrient imbalance, low level of base saturation, high concentrations of Al, Fe and Mn in soils, high P fixation, and domination of low activity clays. The problems could be managed by the application of liming. But, liming calculated on the basis of lime requirement (LR) is not cost effective. However, liming @ 1/10 LR (4-5 q ha^{-1}) applied on the rows to each crop is inexpensive and effective. Apart from calcitic and dolomitic lime stones, industrial wastes such as lime sludge from paper mills, basic slag from steel mills, blast furnace slag, press mud, cement, and kiln wastes could be potential amendments. Another possibility is to grow acid tolerant plant species and cultivars, which have already been identified. As diabetic in human being is not curable but one has to live with it through medicines and other health practices it, so is soil acidity!

Keywords Amelioration • basic slag • liming • lime sludge • soil acidity

Introduction

Orissa is situated between $17^0 47^/$ to $22^0 33^/$ N latitudes and $81^0 21^/$ to $87^0 30^/$ longitude covering 1557 million hectares geographical area, of which 8.67 M ha is acidic. Out of 6.1 M ha cultivated area, about 70 percent area is acidic. Orissa has wide variations in climate, geology, land forms and vegetation, which give rise to large variations in soils. Out of 1482 mm annual average rainfall, 85 percent is received during July through October. In the state, the mean annual temperature is 26.2^0 C, mean summer temperature is 30.3^0C, and mean winter temperature is 21.3^0 C.

Based on stratigraphy, tectonic history, relief feature, and erosion process, the state represents four broad and well-defined physical regions viz. Northern plateau, Central tableland, Eastern Ghats and Coastal plains. The geological sequences responsible for the present topography are the Archean to Recent

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through Pleistocene. The Archeans dominate the rock system with other system like Proterozoic, cretaceous and carboniferous. Integrating the effects of land form, topography, climate, soil and crop adaptability the state has been divided into 10 Agro Climatic Zones. The National Bureau of Soil Survey and Land use Planning (NBSS & LUP) in cooperation with the Soil Conservation (Survey) Department have categorized the soils of Orissa into 3 Agro-Ecological Regions, and 6 Agro-Ecological Sub-regions (Sehgal et al. 1993). This is based on the variability in rainfall, potential evapo-transpiration and actual evapo transpiration.

The soils of Orissa belong to 4 orders as per Soil Taxonomy. Inceptisols (7.49 m ha), Alfisols (5.62 m ha), Entisols (1.53 m ha), and Vertisols (0.93 ma ha) constitute 48, 36, 10 and 6 percent of geographical area, respectively. Red soils (Haplustalfs, Rhodustalfs and Ustorthents) have extensive coverage of 7.14 m ha. The dominant clay minerals are kaolinite and illite in these soils. The soils are mildly acidic in reaction. Mixed Red and yellow soils (Haplustalfs, Paleaustalfs, Ustochrepts) constitute 5.5 m ha and are moderately acidic. Laterite soils (Hapustalfs, Plinthustalfs, Orchaqualfs) constitute 0.70 m ha and are mildly to strongly acidic. Coastal saline soils (Haplaquepts and Haloquents) constitute 0.25 m ha. Some of these soils are mildly acidic. Brown forest soils (Haplustalfs, Ustochrepts and Rhodustalfs) constituting 0.17 m ha are acidic. Apart from these acid soils there are Black soils, Deltaic alluvial soils, mixed red and black soils, which are mildly acidic to slightly alkaline.

The major degradation problems of soils of Orissa are water erosion due to undulating terrain and heavy precipitation, and water logging and salinity in the coastal area. The anthropogenic processes are excessive irrigation, deforestation, and indiscriminate industrial growth. Exploitation of natural resources with little consideration for maintenance of the eco-balance has been very harmful. It is estimated that 6.12 m ha representing 39.3% of the total geographical area in Orissa are affected by various soil degradation process.

Development of acid soil

Acid soils occupy about 30 percent of cultivated land in India, whereas 70 percent of the cultivated land in Orissa is acidic. Acid soils have poor base saturation; which generally varied from 16 to 17 percent in the pH range of 5.0 to 6.0. The active species of naturally occurring ions bound to the clay are H^+ and Al^+. The KCI extractable Fe has minor role in soil acidity compared to Al. Humic acid, hymetamalonic acid, fulvic acid and humus contribute to acidity in various ways. The total acidity of the soil extracted by $BaC1_2$–TEA comprises pH dependent acidity and exchange acidity. The pH dependent acidity (variable charge) calculated as the difference between total and exchange acidity increased linearly with increasing free Fe_2O_3+$A1_2O_3$ plus organic carbon in soil (Mishra et al. 1989).

Since the organic carbon contents were lower (0.29–1.19%) than the sum of free oxides of Fe+A1 (0.7–11.0%), the pH dependent acidity, constituting more than 81 percent of total acidity in the soil was ascribed mainly to inorganic compounds.

Problems associated with acid soils

The most common of the problems in acid soils in respect of chemical properties are low pH, low CEC, nutrient imbalance, low level of base saturation percentage, high Al, Fe, Mn saturation percentage, high P fixing capacity, and clay fraction constituting of rather surface inactive minerals. All these problems could be managed by liming, which improves base status, inactivates Fe, Al, and Mn in soil solution and reduces P fixation markedly (Panda and Kosy 1982). Improvement of availability of soil- and fertilizer-P by liming were reported by Panda and Panda (1969), and Panda and Mishra (1970). Management of acid soils should aim at realization of production potential either by addition of amendment or manipulation of agricultural practices.

Soil acidity in the uplands, which is caused mostly by leaching losses of bases and high percolation of water, create problems of crust formation particularly in light textured red soils. It adversely affects the seed emergence. Such problem could be managed by compaction with heavy iron rollers giving 4 to 6 passes. Straw mulching in the seed lines, particularly in cotton, soybean, cowpea and fingermillet is helpful. Water retentivity of red and laterite soils could be improved by addition of tank silt and clay.

Plant nutritional problems associated with soil acidity

The acid soils of Orissa are deficient in available-N, low to medium in available-P and medium to high in available-K. Barring the soils of Bolangir, Sonepur, Kalahandi, Nuapara, Balasore and Bhadrak districts all other soils are mildly to highly acidic. Total N content varied between 260-1180 mg kg^{-1} in virgin soils and 300-900 mg kg^{-1} in cultivated soils. Organic carbon varied from 0.62 to 1.10 percent in red soils, and from 0.9 to 1.05 percent in laterite soils (Sahu et al. 1983). In the laterite soils (Udic Ustochrepts) under the rice-rice cropping system total N was 1316 kg ha^{-1} and mineralisable N was 188 kg ha^{-1}. The hydrolysable ammonia was 23 kg ha^{-1}, amio sugar 38 kg ha^{-1}, amino acid N 281 kg ha^{-1}, unidentified hydrolysable fraction 344 kg ha^{-1} and total hydrolysable N was 866 kg ha^{-1}. Most of the Red and laterite soils of Orissa are low in available P (Bray-1P; 1.3 to 5.9 mg kg^{-1}) although total content is adequate (Panda and Mishra 1969). P fractionation studies conducted under long term experiments in a rice-rice cropping sequence in laterite soils showed that residual P mostly accumulated as the Fe-P > reductant soluble P>Al-P fraction. Results of multiple regression and path analysis indicated the reductant soluble P and Fe-P directly and Al-P indirectly contributed towards Olsen's P of the soil. Availability of both native and applied water soluble P is low in the predominantly acidic soils of Orissa due to their high P fixing capacity. P fixation capacity increased with free Fe_2O_3+$A1_2O_3$ content.

Potassium status of acid soils of Orissa is medium to high. The annual crop removal of K from soils of Orissa was 282.3 x 10^3 tonnes and addition through fertilizer is only 39.5 x 10^3 tonnes leaving a huge negative balance of 242.9 x 10^3 tonnes (Mishra and Mitra 2001). This accounted for a negative balance of 29.2 kg ha^{-1}. The NH_4OAc extractable K of surface soils did not reflect the large negative balance of K because of a substantial contribution from non-exchangeable mineral fractions. Red soils are adequate and laterites soils are low in K.

Calcium deficiency rarely occurs as a field problem. It is usually the most dominant cation in the soil even at low pH and also principal cation moving down through leaching. Calcium deficiency however occurs in acid sandy soil of humid regions. The calcium deficiency has been observed in light textured sandy soils of Khurda, Mayurbhanja, Sundargarh, Koraput and Dhenkanal districts. Peanut yields have been drastically reduced in the acid course textured soils due to Ca deficiency. Liming @ 1/10 lime requirement work more as Ca source rather than correcting soil acidity. Limited work has been done on magnesium, as its deficiency is uncommon. Results of long-term fertilizer (LTF) experiments showed that available Mg status of the soil decreased from initial value of 142 mg kg^{-1} to 106 mg kg^{-1} after raising 41 crops of rice without addition of any fertilizer.

The total S content of different soil groups was in the range of 25.7 to 925.0 mg kg^{-1}. The light textured red and lateritic soil with low clay context contained less total S. Organic S constituted 66.5–98.3 percent of total S. The red and laterite acid soils had significant positive correlation between clay content and total S (Mishra et al. 1990).

Increased use of high yielding crop varieties, increase in cropping intensity, use of high analysis chemical fertilizers without application of organic manure and unbalanced use of fertilizers have resulted in rapid depletion of micronutrient reserves of the soils of Orissa. The decreasing trend of yield of many crops in recent years is partly due to deficiency of specific micronutrient. The soils are generally deficient in B and Mo and partly in Zn. They are mostly rich or sufficient in Fe, Mn and Cu (Sahu and Mitra 1992). After raising 41 crops of rice, it was observed that DTPA-Zn decreased to value below the critical limits (Table 1). Available Fe, Mn and Cu decreased in control plots. There was decrease in hot water soluble B in all the treatments (Sahu 1997). All the soils had adequate Fe, Mn and Cu. Deficiency of B was high (69.6%) in light textured uplands due to leaching of soluble boron caused by soils acidity. More than 80 percent of acid soils were deficient in available-Mo, 19 percent were deficient in available-Zn whereas only less than 2 percent were deficient in available forms of Cu, Fe, and Mn (Sahu and Mitra 1992).

Table 1 Effect of treatments on available secondary and micronutrient status of soil (after 41 crops)

Treatment	Av. S kg ha^{-1}	Av. Ca kg ha^{-1}	Av. Mg kg ha^{-1}	DTPA -zn mg kg^{-1}	DTPA -Mn mg kg^{-1}	DTPA -Fe mg kg^{-1}	DTPA -Cu mg kg^{-1}	Av. B mg kg^{-1}
100% NPK	38.3	652	122	0.40	5.3	171	1.8	0.30
100% NPK+Zn	40.7	668	151	3.40	6.1	230	2.0	0.32
100% NPK+FYM	41.8	848	214	1.20	10.1	254	2.6	0.45
100% NPK (-S)	11.6	324	103	0.60	3.6	213	1.8	0.32
Lime+LPK (Soil Test)	47.7	956	139	0.60	8.4	136	1.9	0.36
Control	19.7	376	106	0.50	6.8	76	1.2	0.28
Initial (1972)	34.0	492	142	1.44	7.8	53	1.4	0.50

Source: Sahu D 1997 Appraisal Report QRT (1972-96) Long Term Fertiliser Expts, Bhubaneswar

Liming acid soils: Scopes and limitations

Management of acid soils should aim at realization of production potential either by addition of amendments or by manipulation of agricultural practices to derive optimum crop yield even in acid conditions. By liming exchange acidity is deceased but a small amount of lime could neutralize pH dependant acidity. Liming produced significant effect on wheat, maize, pulses and oilseeds (Panda and Das 1971; Mathur 1992). Acidic rice lands, where mono cropping is practiced need not be limed but about 25 percent of the rice soils in India (9.2 M ha), where multi-cropping with pulses and oilseeds is done require to be limed.

Among the naturally occurring lime sources, calcitic, dolomitic and stromatolytic limestones are important. But the former two have industrial uses and hardly have prospects of being economically used as agricultural lime. Lime stone containing more than 47 percent CaO and above are usually preferred in the manufacturing of cement. Orissa has a limestone reserve of 1682 M tonnes. Stromatolytic limestone is a poor grade lime, which contains 28-32 percent CaO, 12 percent MgO and 0.5 percent P. The algal deposits in it contribute to its P content (Panda and Mishra 1970). High silica content restricts its use in industry and hence is good for agriculture. Estimated reserve of such material is 40 M tonnes in Orissa.

Industrial wastes as amendment for acid soils

Several industrial wastes such as steel mill slag, blast furnace slag, lime sludge from paper mills, press mud from sugar mills using carbonation process, cement kiln wastes, precipitated $CaCO_3$ from fertilizer factories have been successfully and economically used as amendment for acid soils, which are also eco-friendly (Panda and Das 1971). Lime sludge contains 65-84 percent $CaCO_3$, 2 percent R_2O_3 and 1.5 percent free alkali. The paper mills located in the acid soil regions of Assam, Nagaland, West Bengal, Orissa, Chhatishgarh and Andhra Pradesh produce 182,000 tonnes of sludge annually, which could be utilized taking into consideration the cost of transport and economics. Basic slag is the double silicate phosphate of lime. It is estimated that for every ton of hot metal 500 kg of blast furnace slag is produced whereas 200-250 kg SMS is produced for every tonnes of steel. The steel mills located at Bhilai, Rourkela, Bokaro, Durgapur, and Burnpur generate about 100 m tonnes of slag annually of which very small quantity goes to manufacturing of black cement. Indian slogs contain 24-42 percent CaO and 2-10 percent MgO.

Agro techniques for reducing phosphate fixation and improving fertilizer use efficiency in acid Soils

The cost of P fertilization in acid soils can be reduced by direct use of ground rock phosphate or in combining it with a small proportion of water soluble P from super phosphate. By such a combination initial P need at the early seedling stage is satisfied by water soluble P and later rockphospate releases P when enough acidity is created in the rhizospher (Panda and Panda 1969). Most indigenous rock phosphates of sedimentary origin are of poor quality for economic processing to water-soluble form. Partial acidulation of rock has been observed to be possible means for economic and efficient utilization of indigenous rock Phosphate (Panda and Mishra 1970). Udaipur rock phosphate containing substantial amount of dolomite and calcite, served as amendment when applied directly to acid soils. Highly reactive imported rock phosphate such as North Carolina rock could work as a starter for crops grown in acid soils mixed with higher proportion of indigenous rock. In the acid soils the activity of non-symbiotic free-living bacteria, non-symbolic free-living blue green algae and symbiotic rhizobia could be improved by application of lime, phosphorus and molybdenum. Liming reduces the activities of fungi and increases the activity of bacteria and actinomycetes facilitating nitrification.

Management of acid soils having iron toxicity

Iron toxicity of low lying rice fields in red and laterite soils could be remedied by providing deep drains around the rice fields and construction of check embankment across the slope and diverting the ferrous iron through diversion weirs. Modest application of lime on the soil surface to control acidity temporarily

is also recommended. Use of Udaipur rock phosphate, which contains good amount of dolomite and calcite helped in rectifying iron toxicity. Application of about 60 kg K ha^{-1} to create an oxidizing zone around the rhizosphere holds good in checking conversion of Fe^{3+} to Fe^{2+}.

Selection of crop species and cropping systems for acid soil region

In view of high lime requirement of acid soils, which is not cost effective, sustainability of such practice remains questionable. This is more so because heavy rains of 1500 mm during the three months period either take out lime through the surface runoff or leaching down. Therefore, its alternative is to grow acid tolerant plant species and cultivars. Rice has tolerance to soil acidity because of flooding of rice fields. The rainfall distribution system in the sub humid tropics compels the farmers to grow rice in medium and low land in kharif (wet) season because the major portion of the annual precipitation is received through July to September and fields remain ponded with standing water. In the post rainy season some pulses, oilseeds and vegetables those have established themselves by the process of natural selection are grown with the help of residual moisture. Poor response of crops like minor millets, finger millets to liming indicates their tolerance to acidity. The crops, which show moderate response to liming, are Bengal gram, peanut, corn, sorghum and field peas. Crops like soybean, pigeon pea, cotton responded well to liming indicating high sensitivity to acidity. Rainfall and moisture storage capacity of soils determine the cropping patterns. Crop diversification is confined to uplands where rice, corn, finger millet, pearl millet, sorghum, pigeon pea, mesta and niger are grown as alternative crops and at times as a mixture.

Scope of integrated nutrient management system (INMS) in acid soils

The basic principle of INMS is the maintenance of soil fertility, sustainable agriculture productivity and improving profitability through judicious and efficient use of chemical fertilizers, organic manures, green manures, and bio fertilizers. Reliance on chemical fertilizers for sustainable agricultural development would have to continue in spite of the environmental threats, real or imaginary. Though bio fertilizers can increase yields significantly, its benefit in the acid soils is restricted. Rhizobia culture is beneficial for pulses like green gram, black gram, peas and oilseeds like soybean and peanuts. But soil acidity is not compatible to growth of rhizobia. Low base status and poor availability of P in acid soils come adversely on the way of efficient rhizobia culture. Blue Green Algae (BGA) performs poorly when the soil is highly acidic. Frequent BGA application in rice is necessary since acid soils are incapable of maintaining high BGA population. Since acid soils have high P fixing capacity, the P requirement of azola ordinarily cannot be met.

Liming on the basis of lime requirement is highly expensive and not cost effective. Hence such a technique is not acceptable to poor farmers. However, a cheaper method evolved by the OUAT, Bhubaneswar and BAU, Ranchi, involving application of 4-5 q ha^{-1} of Lime (1/10 LR) on rows was acceptable. This technique was tested on 871 farmers field trials spread over NE States, Assam, West Bengal, Orissa, Jharkhand, Chhatisgarh, Himachal Pradesh, and Maharastra with encouraging results. Yields of different crops increase by 14 to 52 percent over farmers practice (Figs. 1 & 2).

The conjunctive use of lime and NPK through chemical fertilizer raised the

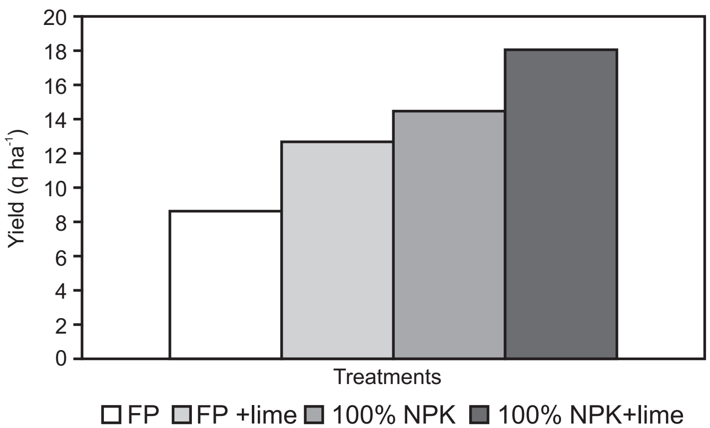

Fig. 1 Response of groundnut to liming and fertilization in acidic soils of Orissa

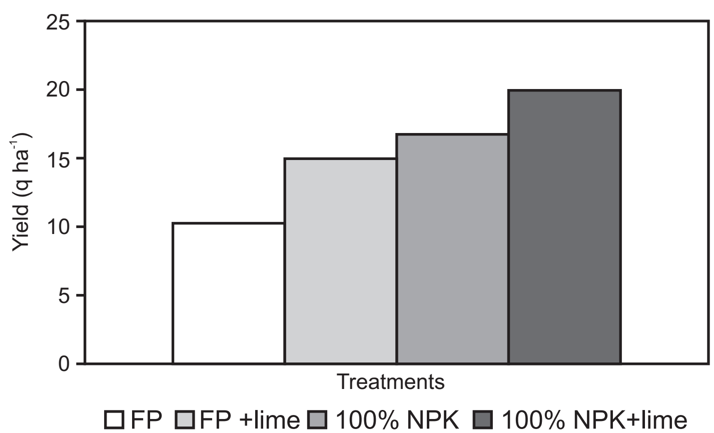

Fig. 2 Response of pigeonpea to liming and fertilization in acidic soils of Orissa

yields by 49 to 189 percent. The mean benefit cost ratio was 2.5, which varied from 1.4 to 4.3 with the conjunctive use. By such a practice the poor farmers of Orissa who ordinarily own the infertile, low water retentive uplands could be benefitted immensely (Sharma and Sarkar 2005). Under the climate and field conditions of Orissa soil acidity cannot be reclaimed but certainly it could be ameliorated for higher production. Orissa grows 5.8 lakhs ha of leguminous kharif pulses and 3.9 lakhs ha kharif oilseeds with an average productivity of 527 and 661 kg ha^{-1} respectively. Though results from the farmer's plots showed 44-45 percent yield increase by only amending such acid soils with lime, even if a discounted increase of 20 percent is taken, the increase in kharif production would be of the order of 61000 tonnes in case of pulses and 51000 tonnes oilseeds without any addition of fertilizer, which should suit to the economically distressed small and marginal farmers of the State.

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Potassium nutrition of crops under varied regimes of nitrogen supply

Fusuo Zhang • Junfang Niu • Weifeng Zhang • Xinping Chen • Chunjian Li • Lixing Yuan • Jianchang Xie

Abstract Nitrogen (N) over-application is a serious problem in intensive agricultural production areas with consequent large N losses and environmental pollution. In contrast to N, potassium (K) application has been neglected in many developing countries and this has resulted in soil K depletion in agricultural ecosystems and prevented increases in crop yields. Nitrogen-potassium interaction is currently a topic of interest in many studies and the focus of this review is K nutrition under varied N regimes. Nitrogen form and application rate and time influence soil K fixation and release, as well as K uptake, transport, cycling and reutilization within crops. High yielding quality crops can be obtained by optimal N: K nutritional ratios. High rates of applications of N and K do not necessarily lead to increased yield increments and may even reduce yield. Yield response to K uptake depends on N nutritional status and the interaction is usually positive when NO_3^--N is supplied. Antagonism between NH_4^+ and K^+ in uptake was mostly attributed to simple competitive effects in the past while evidence showing mixed-noncompetitive interactions existed. Two components of membrane transport systems for K uptake by plants are a high-affinity K^+ transport system which is inhibited by NH_4^+ and a low-affinity K^+ transport system which is relatively NH_4^+ insensitive. Potassium is highly mobile within plants but its flow and partitioning can change depending on the forms of N supply. NH_4^+ nutrition in comparison to NO_3^- supply results in more K translocation to leaves. A better understanding of the mechanism of N-K interaction can be a useful guide to best

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nutrient management in agricultural practice in order to achieve high yields with high nutrient use efficiency.

Keywords Potassium-nitrogen interaction • potassium transport and cycling • ammonium • nitrate

Introduction

Potassium is an important essential macronutrient for plants which, with N and P, plays an important role in plant development. Potassium has a wide range of functions in plant nutrition, including the maintenance of electrical potential gradients across cell membranes, the generation of turgor, and the activation of numerous enzymes. It is also essential for photosynthesis, protein synthesis, and regulation of stomatal movement, and is the major cation in the maintenance of anion-cation balances (Marschner 1995). Potassium nutrition in crops is influenced by cultivation practices, crop species and environmental conditions such as soil type and climatic conditions. Nitrogen, in terms of its requirement and management in the field, is the most important nutrient for all crop plants. Over-application of N is a serious problem in intensive agricultural production areas because this leads to enrichment of reactive N constituents into the atmosphere, soil and water with consequent impairment of ecosystem services. Current fertilizer N application rates of 550-600 kg N per hectare annually in Taihu region of east China and on the North China Plain could be cut by 30 to 60% while still maintaining crop yields and N balance in the rotation and substantially reducing N losses to the environment (Ju et al. 2009). Compared to N, application of K has been neglected in many developing countries including Asian countries and this has resulted in the continual depletion of soil K (Regmi et al. 2002; Panaullah et al. 2006; Ladha et al. 2003; Wang et al. 2007b; Lal et al. 2007). Frequent K deficiency has been observed in crops in these regions (Dobermann et al. 1996; Panaullah et al. 2006; Mussgnug et al. 2006). Regmi et al. (2002), suggested that because of inadequate K application soil K imbalance in agricultural ecosystems and stagnation of yields will become more pronounced with time (Regmi et al. 2002). In China the increase in K fertilizer consumption has been much lower than that of N fertilizers although in recent years it has increased rapidly (Fig. 1).

Many long term experiments have shown that high yields can be achieved from balanced NPK supply (Belay et al. 2002; Cai and Qin 2006; Wang et al. 2007a). To ensure sustained crop production under intensive cropping, application of recommended doses of NPK plus FYM is required (Rupa et al. 2001). Nitrogen application rate, timing and N source influence the K nutrition of crops and the interaction of these factors with K nutrition has been found to be significant in numerous studies**.** Optimal N and K application is propitious to best nutrient management in agriculture. A nitrogen-potassium interaction generally exists in

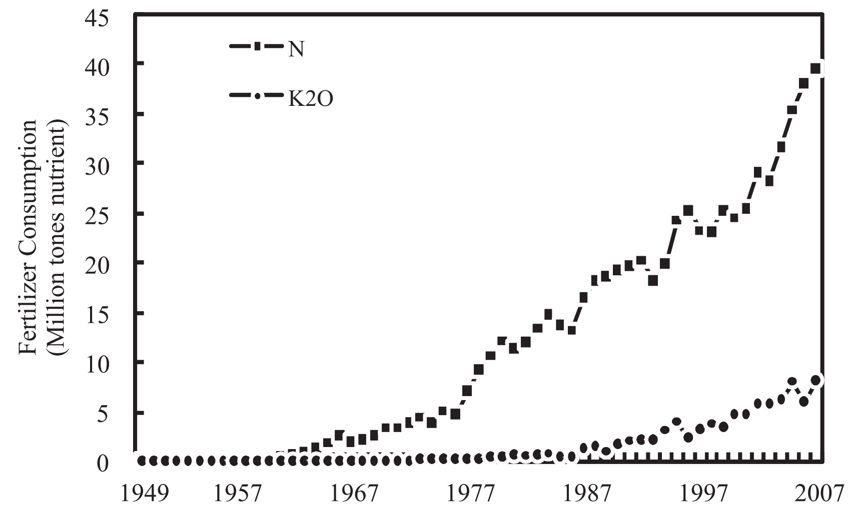

Fig. 1 Trends in fertilizer consumption in China from 1949 to 2007 (According to China Agriculture Yearbook)

agricultural ecosystems (Gething 1993; Johnston and Milford 2009). In this paper we review K in crops under varied N regimes, including effects of N-K interaction on crop yields, and processes of N-K interaction such as K uptake, transport, recycling and reutilization within plants under different levels of N supply. We also consider N-K interactions in relation to soil-K fixation and release under varied N regimes as well as their influence on crop yield, quality and stress tolerance in order to provide a guide to best nutrient management in agriculture.

Processes of N-K interaction in the soil-crop system

Soil-K fixation and release under variable N regimes

Soil K status influences K uptake by plant roots. The amount of K removed by plants depends on the production level, soil type, and the retention or removal of crop residues (Yadvinder-Singh et al. 2005). Even if the soil is rich in K, it becomes K deficient under conditions where no K is supplied, because of the continuous K removal during uptake by crops (Rupa et al. 2001; Cai and Qin 2006). On the other hand, a small build-up in available K was observed in K amended plots notwithstanding the negative balance of K, based on the approach of the input-output relationship (Benbi and Biswas 1999). There was a shift in the equilibrium from the non-exchangeable to the exchangeable and soluble forms in the soil K pool. Potassium uptake during plant growth is a dynamic process with periods of

K^+ depletion in the root zone and release of non-exchangeable K^+ to exchange and solution phases by K^+ bearing soil minerals (Jalali 2006). The process of K^+ release is initiated by a low K^+ concentration in the soil solution and not by cation exchange (Jalali 2006).

Release and fixation rates of K in soil are highly dependent on the soil K balance, confirming that these are reversible processes that depend on plant uptake and fertilizer inputs (Simonsson et al. 2007). Crop K requirement under negative soil K balance due to imbalanced NPK fertilization in intensive cropping systems is mainly met through K released from non-exchangeable sources (Rupa et al. 2003; Lal et al. 2007). To meet the crop K requirement, non-exchangeable sources contributed on an average about 95% in the absence of applied K and 65% with added K (Lal et al. 2007). The potassium quantity-intensity (Q/I) plot components, labile K^+, activity ratio for K^+ at equilibrium (AR_K) and linear potential buffering capacity for K^+ (PBC_K) were affected by tillage and N additions (Evangelou and Blevins 1988). The highest and lowest PBC_K values were in conventional tillage with no N at 0–50-mm depth and no-tillage with no N also at the same depth (Evangelou and Blevins 1988). The values of AR_K, the activity ratio of K in soil solution inequilibrium with the soil, non-specific or immediate available K were observed in the following order: NPK+FYM (Farmyard mature) >NPK>control> N>NP (Rupa et al. 2003). The scale of Q/I plot indices, which were affected by tillage and N additions, indicated the potassium nutritional status in the soil and the ability to supply potassium to crops.

Levels of exchangeable K and both NH_4^+ and K^+ fixation capacities are influenced by long-term fertility management (Liu et al. 1997). Fixation capacities for both NH_4^+ and K^+ were significantly reduced by sustained high rates of K fertilization, but not by N fertilization (Liu et al. 1997). Simultaneous proximal injection of anhydrous ammonia (AA) and KCl solution in a Hoytville silty clay loam soil, however, has been shown to increase exchangeable and solution K^+ (Stehouwer and Johnson 1991; Stehouwer 1993). Decreased K^+ fixation was attributed to preferential NH_4^+ fixation blocking K^+ fixation. Increased exchangeable K^+ was attributed to pH-induced increases in cation-exchange capacity (primarily in the organic fraction), and to decreased K^+ fixation (Stehouwer and Johnson 1991; Stehouwer 1993).

NH_4^+ fixation was increased with increased N rates and was reduced with increased K rates with urea. With NH_4Cl application, an increase in fixed NH_4^+ was noted with increasing K rate (Chen and MacKenzie 1992). By contrast, K^+ fixation was enhanced consistently with increasing K application rate and decreased with increasing N application rate (Chen and MacKenzie 1992; Du et al. 2007). But other research found that the fixation of NH_4^+ was reduced by K addition before NH_4^+, and the reduction was proportional to the amount of K previously fixed

(Kenan et al. 1999). In the presence of K, NH_4^+-N concentrations increased 4.1 fold when N fertilizer was applied and 3.5 times in the absence of N application (Tung et al. 2009). Compared with application of K^+ alone, addition of NH_4^+ did not show any effects on diffusion distance of fertilizer K but did increase the concentration of water extractable K in fertilizer microsites (Du et al. 2007). In the soil close to the fertilizer placement site the concentration of exchangeable K decreased as a result of the NH_4^+ addition, and this was less apparent in Flurvo-aquic soil than in red soil. The addition of NH_4^+ reduced K fixation in soil crystal lattices, thereby increasing the risk of K leaching in the soil (Du et al. 2007).

N sources and the sequence of NH_4^+ and K application influence K fixation (Chen et al. 2007). NH_4^+ application before K fertilization at high rates resulted in poor rice growth compared to NH_4^+ application after K fertilization (Fig. 2). However, when nitrate was used as the N source plant growth was not affected by the order in which N and K were applied (Chen et al. 2007).

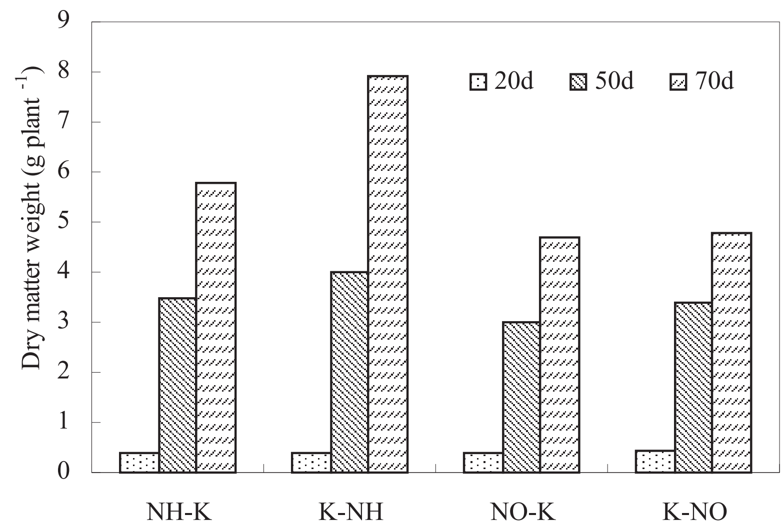

Fig. 2 Effects of N source and the order of N and K application on rice growth (adapted from Chen et al. 2007) NB: NH-K, K-NH, NO-K, and K-NO indicate NH_4^+-N application before K fertilization, NH_4^+ application after K fertilization, NO_3^--N application before K fertilization and NO_3^--N application after K fertilization, respectively.

Low K use efficiency often happens as the result of soil K leaching losses, even especially in the subtropical regions with sandy soils and heavy rainfall. K leaching losses are related to soil mineralogy, soil textures, rainfall pattern, fertilizer treatments, corresponding anion leaching, level of exchangeable K in the soil and nutrient uptake by roots (Hombunaka and Rowell 2002; Alfaro et al. 2003, 2004; Kayser et al. 2007; Tung et al. 2009). At the present of N, K leaching is decreased because that N increases K uptake by plants (Tung et al. 2009). Urea is the major N form in agriculture in arid and semiarid regions. When urea is applied to a soil, it is hydrolyzed to ammonium carbonate. In carbonate-bearing soil, the acid produced by nitrification of ammonium carbonate gives rise to an increase in concentration of Ca^{2+} and Mg^{2+} in the soil solution, which could exchange with other cations, including K^+. Therefore, application of urea to agricultural soils leads to increase K^+ leaching (Kolahchi and Jalali 2007). A new nitrification inhibitor 3,4-dimethylpyrazole phosphate (DMPP) supplementation results in less K leached significantly when ammonium sulphate nitrate (ASN) ($(NH_4)_2SO_4$ and NH_4NO_3) are supplied as the nitrogen form in the sandy loam soil due to lack of NO_3^- as the counter ions (Wu et al. 2007). However, there are other reports that the N addition alone had no significant effect on K leaching. But addition of N together with the high CO_2 treatment significantly reduces K losses (Liu et al. 2008). It is speculated that forests in subtropical China might suffer from K limitation and reduction in plant biomass under elevated CO_2 concentration due to mineral leaching losses in the future.

K uptake and content in plants under variable N regimes

Crop biological yields increase significantly with N and K application. The highest biological yield of wheat was obtained by foliar application of KCl along with N as urea compared with other treatments, namely, the control (no spay), KNO_3, KCl, and N as urea only (Khan et al. 2006). A positive N-K interaction has been reported in many long term experiments (Belay et al. 2002; Cai and Qin 2006; Wang et al. 2007a). Response to K applications in both rice and wheat increases with N application, indicating that higher K rates are required at higher N rates (Mondal 1982). Adequate K accelerated N uptake and its assimilation in mustard plants (Mohammad and Naseem 2006; Table 1). Potassium application enhanced the activities of leaf carbonic anhydrase (CA) and nitrate reductase (NR), thereby inducing efficient photosynthesis and the formation of primary organic N-containing molecules necessary for amino acids required for protein synthesis (Table 1).

In the same manner, recovery efficiencies of K (RE_K) and N fertilizer on maize increased at 105-150 kg K_2O ha^{-1} and 195-240 kg N ha^{-1} for K and N positive interactions on nutrient uptake and yield (Xie et al. unpublished data; Table 2). However, RE_K and nitrogen use efficiency increase were reduced at 195 kg K_2O ha^{-1} when the N application rate was raised to 255-312 kg N ha^{-1} (Table 2). Optimal N-K ratios favored crop growth and enhanced K and N use efficiency.

Table 1 Effect of K on activities of leaf carbonic anhydrase (CA) and nitrate reductase (NR), net photosynthetic rate (P_N) and NO_3^- contents and yield of mustard (Mohammad and Naseem 2006)

Characteristics	Potassium [mM K]						
	5	10	15	20	25	30	CD at 5%
CA activity [µmol(CO_2) kg^{-1} (leaf f.m.) s^{-1}]	205.7	231.3	249.1	285.4	262.6	255.8	16.1
NR activity [pmol(NO_2) kg^{-1} (leaf f.m.) s^{-1}]	29.6	33.7	34.7	35.9	32.3	31.6	2.3
P_N [µmol(CO_2)$m^{-2}s^{-1}$]	9.3	10.8	12.4	13.9	13.3	13.5	1.0
N content (%)	2.5	2.6	2.6	2.8	2.9	2.9	0.2
Dry mass $plant^{-1}$ (g)	1.7	2.6	2.7	3.1	3.0	3.1	0.2

Table 2 Recovery efficiency of K fertilizer and increase of N use efficiency in maize (n=3) （Xie et al. unpublished data）

Treatment*	Recovery efficiency of K (%)**		N use efficiency increase (%)***	
	Range	Mean	Range	Mean
N1K0	-	-	-	-
N1K1	26.7~39.5	33.8	9.4~22.3	14.8
N1K2	38.3~42.7	40.5	20.7~25.1	22.2
N1K3	39.2~43.6	38.3	20.7~36.7	29.7
N2K0	-	-	-	-
N2K3	29.0~38.2	29.3	12.2~25.1	18.3

* These experiments were conducted in Suiping and Xiping County, Henan Province, and Feidong County, Anhui province. The N1 and N2 rates were 195-240 and 255-312 kg N ha^{-1}. The K1, K2 and K3 rates were 105,150 and 195 kg K_2O ha^{-1}.

** Recovery efficiency of K (%) =Plant K uptake (K fertilized–K unfertilized)/fertilized K amounts ×100.

*** Increase of use efficiency of N (%) = Plant N uptake (K fertilized – K unfertilized) / fertilized N amounts ×100.

The positive N-K interaction is also dependent on the form of nitrogen supplied. Nitrate uptake has been shown to stimulate net K^+ uptake in various crop species, suggesting that the NO_3^- ion serves as a mobile accompanying anion during K^+ uptake and/or transport (Pettersson 1984; Zsoldos et al. 1990). It has been reported that NH_4^+ reduces K^+ uptake in plant roots (Scherer et al. 1984; Wang et al. 2003; Lu et al. 2005; Guo et al. 2007) because NH_4^+ and K^+ have similar charges and hydrated diameters (Wang et al. 1996). K depletion of the nutrient solution enhances the absorption of NH_4^+-N but in contrast suppresses the absorption, translocation, and assimilation of NO_3^--N, simultaneously lowering leaf nitrate reductase activity (NR). This behavior suggests that plants require an adequate supply of K for absorbing NO_3^--N and maintaining high levels of NRA as compared with the assimilation of NH_4^+-N (Ali et al. 1991). Compared with NO_3^- nutrition, supplying both forms of N (NO_3^- plus NH_4^+) increased whole plant and/or shoot accumulation of K (Wang and Below 1998). Potassium activates plant enzymes functioning in ammonium assimilation and transport of amino acids (Hagin et al. 1990). Therefore, an adequate supply of K enhances ammonium utilization and thus improves yield when both N forms are applied together (Hagin et al. 1990).

There have been numerous studies on NH_4^+-K interactions in different crops. K^+ may alleviate NH_4^+ toxicity by inhibiting NH_4^+ uptake and/or by stimulating C and N assimilation in the roots (Roosta and Schjoerring 2008). The chemical similarity and identical ionic status of the NH_4^+ and K^+ ions suggest possible substrate competition via a transport system (Jarvis 1987; Guo et al. 2007). However, contradictory observation on the effect of K^+ on NH_4^+ uptake has been reported. Scherer et al. (1984) reported that NH_4^+ inhibits K^+ uptake in plant roots, but NH_4^+ uptake rate did not recover when K^+ was removed, suggesting mixed-noncompetitive interactions between K^+ and NH_4^+. There are two components of K uptake by plants which have different sensitivities to NH_4^+ and will be mentioned in the next section. An enhanced efflux of K^+ coupled to NH_4^+ influx via an antiporter cannot be ruled out, which would contribute to the decrease in net K^+ uptake (Scherer et al. 1984). The inhibitory effect of ambient NH_4^+ on net K^+ uptake resulted from an initial but temporary enhancement of K^+ efflux and a constant inhibition of K^+ influx (Topa and Jackson 1988). This negative interaction also depended on ion concentrations. Potassium influx was restricted progressively as ambient ammonium concentration increased to about 100 micromolar while little inhibition of K influx appeared with ammonium concentrations up to 500 micromolar (Vale et al. 1987). The optimal range of NH_4^+-N concentration (0.9-1.8 mM) in the nutrient solution led to increases in both the total fruit yield and the fertilizer K use efficiency in sweet pepper (Xu et al. 2002).

Many studies have reported that K concentration in crops remained practically unchanged irrespective of N supply. Working with rice and wheat crops Panaullah et al. (2006) observed that the majority of K taken up was present in straw and the proportion in grain (11-29%) varied little across the sites. K concentrations present in ryegrass expressed on both a dry matter and tissue water

basis remained within a narrow range irrespective of treatment or time (Jarvis et al. 1990). The rate of N application had little impact on the K concentrations in ripe grains (Alfoldi et al. 1994). These results show that K concentrations in the grain are well-buffered against increments in grain yield resulting from the application of N and are also relatively insensitive to low supplies of K in the soil (Alfoldi et al. 1994). Contrary to these findings Rui et al. (2009) reported that K was significantly lower in treatments with N fertilizer compared to a control without N fertilizer and a significant negative correlation (R) was observed between K and N fertilizer input -0.89.

Long term K stress for a 3 1/2-month reduced the root capacity to absorb NO_3^- of sugarcane as shown by lower initial NO_3^- uptake rates and lower Vmax and increased Km for NO_3^- uptake at 0.02 and 0.2 m M K (Subasinghe 2006). Long term N stress reduced the initial K^+ uptake rates and decreased the affinity of roots for K^+, as indicated by increasing Km and decreasing Vmax for K^+ uptake with decreasing N availability. Furthermore, there were genetic differences in the response of K^+ uptake to N stress (Subasinghe 2006). A drought and salinity resistant cultivar showed greater adaptability to a low-nutrient environment due to its higher root allocation and affinity for NO_3^- and K^+ under N and K stress, suggesting that the resistance of sugarcane to multiple stresses may involve a general stress-response system (Subasinghe 2006). Potassium deprivation in general induces changes in the relative growth of roots, nodules, and shoots rather than changes in N and/or carbon uptake rates per unit mass or area of these organs (Hogh-Jensen 2003). The mechanism of N-K interaction is complicated and further study is required.

K transport, cycling and reutilization in plants under varied N regimes

Two distinct membrane transport systems for K uptake by plants have been described: a high-affinity transport system (HATS) and a low-affinity transport system (LATS) (Kochian and Lucas 1982; Hirsch et al. 1998). HATS operates primarily at low external concentrations (<1mM) of K^+ by transporters while LATS dominates at higher external concentrations (>1mM) mostly via channels (Maathuis and Sanders 1997; Hirsch et al. 1998; Véry and Sentenac 2002; Szczerba et al. 2006). A large number of genes encoding K^+ transport systems have been identified, revealing a high level of complexity (see reviews by Véry and Sentenac 2002; Szczerba et al. 2009).

Different nitrogen forms influence the activity of the two distinct K transport systems. NH_4^+ inhibits high-affinity K^+ transport (Scherer et al. 1984; Vale et al. 1988; Hirsch et al. 1998; Spalding et al. 1999; Santa-Maria et al. 2000; Ashley et al. 2006; Nieves-Cordones et al. 2007; Szczerba et al. 2008), while low-affinity K^+ transport is relatively NH_4^+ insensitive and takes effect on the alleviation from

NH_4^+ toxicity at high K^+ concentrations (Santa-Maria et al. 2000; Britto and Kronzucker 2002; Kronzucker et al. 2003; Szczerba et al. 2006; Szczerba et al. 2008). A distinct variation in cytosolic K^+ concentrations ($[K^+]_{cyt}$) was observed in plants supplied with nitrate or ammonium N for both HATS and LATS activity (Szczerba et al. 2006). The increase in $[K^+]_{cyt}$ with improving external potassium supply and the rapid and futile cycling of potassium at the plasma membrane were two characteristics in LATS-range cytosolic K^+ pools in contrast to the relative constancy in the HATS range (Kronzucker et al. 2003). At high external potassium concentration (and particularly at 40 mM), cytosolic potassium efflux, an energy-intensive process, was greater with nitrate-grown than ammonium-grown plants (Szczerba et al. 2006).

Potassium is the most mobile ion within plants since most of K is not assimilated in organic compounds. Potassium has the property of high phloem mobility and, as a result, a high degree of reutilization by retranslocation via the phloem (Marschner 1995; Marschner et al. 1997). Cytosolic K^+ concentrations are shown to vary between 40 and 200 mM, depending on $[K^+]_{ext}$, on nitrogen treatment (NO_3^- or NH_4^+), and on the dominant mode of transport (high- or low-affinity transport), illustrating the dynamic nature of the cytosolic K^+ pool (Szczerba et al. 2006). K cycling and recycling play an important part in NO_3^- translocation from root to shoot as counterion and assimilate loading in the phloem (Maathuis 2007). The partitioning and the amount of phloem retranslocation of K^+ from the shoot and cycling through the root are quite different depending on plant type and can be changed by stress (Jiang et al. 2001; Lu et al. 2005).

Moreover, the flow and partitioning of K in tobacco plants can be modified depending on the forms of N supplied and nutrient levels. NH_4^+ nutrition resulted in more K translocated to leaves than did NO_3^- supply in terms of the amounts of xylem-transported potassium in plants (Lu et al. 2005; Zou et al. 2005), although NH_4^+-N as the sole N-source caused a decrease in potassium uptake relative to NO_3^--N supply. When NH_4^+-N was supplied as the sole N-source, massive amounts of K were exported from leaves and cycled in the phloem, especially at low nutrient levels compared to NO_3^--N or NH_4NO_3 supply. NH_4^+-N as the sole N-source also caused a reduction in transpiration rate, changes in plant water use efficiency and a decrease in K uptake (Wang et al. 2003; Lu et al. 2005; Zou et al. 2005). However, there are other reports that roots treated with high levels of NO_3^- absorbed and translocated more K^+(^{86}Rb) than seedlings treated with low levels of NO_3^- (Pettersson 1984; Zsoldos et al. 2006). Cycling and recycling of K^+ increased with increasing shoot growth rate, which is in accordance with the suggested role of K^+ for charge balance of NO_3^- in the xylem and organic acids in the phloem (Engels and Kirkby 2001).

Concentrations of K^+ in the cytoplasm of most cortical cells were generally greater than in the vacuoles and this difference was greater in low NO_3^--fed plants than in those supplied with high NO_3^--N (Jarvis et al. 1990). The changes in K^+ concentration in the cortex were related to the role of K^+ in the transport of NO_3^- in the xylem and effects on recycling to the roots in the phloem (Jarvis et al. 1990).

Interactions may exist between other factors and N nutrition affecting K nutrition. The uptake and accumulation of K^+ in shoots decreased more due to salinity in ammonium-fed plants compared to nitrate-fed plants. By contrast, K^+ cycling in shoots increased due to salinity, with higher rates in the ammonium-treated plants (Abdolzadeh et al. 2008).

Effects of N-K interaction on quality and stress tolerance of crops

Potassium is acknowledged as a nutrient element improving crop quality and protecting plants against abiotic and biotic stress, while excessive N dressings often cause lower quality and higher susceptibility of crops to disease. An important aspect of the N-K interaction, therefore, is its relationship with crop quality and stress tolerance. The highest growth parameters, carbohydrate contents and juice extract of sweet sorghum were obtained with combination of N and K ferilizers (Almodares et al. 2008). Application of K favors an increase in grain protein and amino acid contents (Yang et al. 2004; Venkatesan et al. 2004; Zou et al. 2006b), but responses vary among cultivars (Zou et al. 2006b). Compared with Ningmai 9 (a low-protein wheat cultivar), the role of K in improving the contents of grain protein was greater in Yangmai 10 (a medium-protein wheat cultivar). Protein content in wheat grain showed a close positive correlation with N accumulation and translocation (Zou et al. 2006b). However, in tea crops overall quality was impaired when either N or K was used at high levels (Venkatesan and Ganapathy 2004). There are other reports that the N-K interaction was not significant for concentration of oil or protein in grain of canola although it was always significant for grain production (Brennan and Bolland 2007; 2009). Nitrate contents in vegetables were raised with increasing N supply but decreased with potassium application, especially at high N application levels (Sun et al. 2000; Fig. 3).

At N rates of 150 and 250 mg N L^{-1} in the nutrient solution, fertilization with K (at 440 and 760 mg K_2O L^{-1}) increased vitamin C (Vc) content in tomato, the highest Vc content being achieved in the 250 mg N L^{-1} plus 760 mg K_2O L^{-1} treatment (Fig. 3). However, overall quality of vegetables was impaired when either N or K or both were used at high levels (350 mg N L^{-1} and 1080 mg K_2O L^{-1}) (Fig. 3). The same was also true for tea (Venkatesan and Ganapathy 2004). Adequate K supply and optimum N and K in combination can ensure high quality and high yield production of vegetables. In China nutrient input is very high for

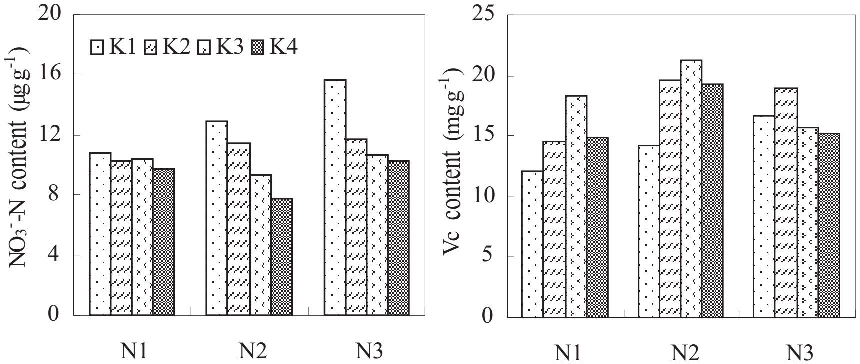

Fig. 3 Effects of K fertilization on nitrate and Vc content of tomato at different N levels (adapted from Sun et al. 2000)

NB: The N1, N2, and N3 rates in the solution were 150, 250 and 350 μg N g^{-1}. The K1, K2, and K3 rates in the solution were 120, 440, 760, 1080 μg K_2O g^{-1}.

both nitrogen and potash in greenhouse vegetable production (Chen et al. 2004; Table 3) and many problems are associated with fertilizer wastage in these fields and this presents serious questions on nutrient management in China.

Table 3 Average nutrient inputs for selected greenhouse vegetable species in China in Beijing suburb from 1996-2000 (Chen et al. 2004)

Species	Samples	N input(kg ha^{-1})	K_2O input(kg ha^{-1})
Cabbage	14	440	132
Chinese Cabbage	65	624	173
Cucumber	94	1012	261
Eggplant	19	1070	339
Sweet pepper	5	1068	283
Tomato	132	787	232

The important role of K in alleviating detrimental effects of abiotic stresses in plants and pest and disease invasions has been reviewed by Cakmak (2005) and Amtmann et al. (2008). Adequate K supply can relieve the damage caused by drought, salt, chilling, high light intensity, and heat (Cakmak 2005). Potassium application increased the grain yield, uptake of K and nitrogen, and water use efficiency in maize over control (Nakashgir 1992). Application of N along with K decreased significantly Na^+ uptake in leaves of sugarcane and increase plant salt tolerance to produce high biomass (Noaman 2004; Ashraf et al. 2008). The beneficial effect of K was most obvious for fungal and bacterial diseases where 70 and 69% of the studies reported a decrease in disease incidence (Amtmann et al. 2008). KNO_3 significantly reduced the severity of Alternaria leaf blight of cotton (Gossypium hirsutum) at the middle canopy level (Bhuiyan et al. 2007). Aggregate sheath spot (AgSS) severity of rice decreased with increasing N and K fertilizer rates and leaf N and K concentrations at particle initiation (Williams and Smith 2001; Linquist et al. 2008). But it was not recommended to over fertilize with N in order to reduce AgSS because over fertilization can increase the severity of other fungal leaf sheath diseases and result in crop lodging and reduced yield. Rather, N fertilizer should be applied with the goal of achieving optimal yields as opposed to maximum yields and advisable amounts of K should be supplied to improve yield and decrease the severity of AgSS diseases when the soil extractable K is low (Linquist et al. 2008).

Effects of N-K interactions on crop yields

Yield response to K uptake depends to a great extent on the level of N nutrition and the interaction is normally positive (Macleod 1969; Blevins 1978; Loué 1978; Guo et al. 2004; Bruns and Ebellhar 2006; Brennan and Bolland 2007, 2009). When moderate N fertilizer was supplied (wheat 112.5 kg N ha^{-1} and cabbage 350 kg N ha^{-1}), yield increments of wheat and cabbage after K application were higher than when N or K fertilizer was applied singly (Figs 4 and 5). Response to yield and the utilization of nitrogen by maize was found to be accentuated when K application was supplemented with farm yard manure (Nakashgir 1992). Moreover, Crop yield response to total applied N was influenced by inherent soil P and K fertility differences (Brye et al. 2007). Increasing the rate of fertigated N when growth was constrained by K deficiency had no effect on ecnomic yield and quality of apples (Neilsen et al. 2004) and cotton plants (Pettigrew et al. 2006). At Rothamsted research station, responses to N application of spring barley were observed on both high and low K soils (Johnston and Milford 2009). The average yields showed that the maximum yield was reached by applying 50 kg N ha^{-1} to a soil with 55 mg kg^{-1} exchangeable K, but yield was further increased by an application of N of up to 96 kg ha^{-1} when the soils contained adequate amounts of exchangeable soil K (Johnston and Milford 2009). These results suggest that a strong interaction between N and K exists in crop growth. However, over-application of N and K does not lead to further yield increments as shown in Figs 4 and 5. Critical and maximum K concentrations are proportional to critical %N throughout growth (Greenwood and Stone 1998). Optimum N: K ratios are in favor of healthy plant growth and development whereas imbalance of N and K supply results in maladjustment of plant growth (Xie 2000; Wells and Wood 2007).

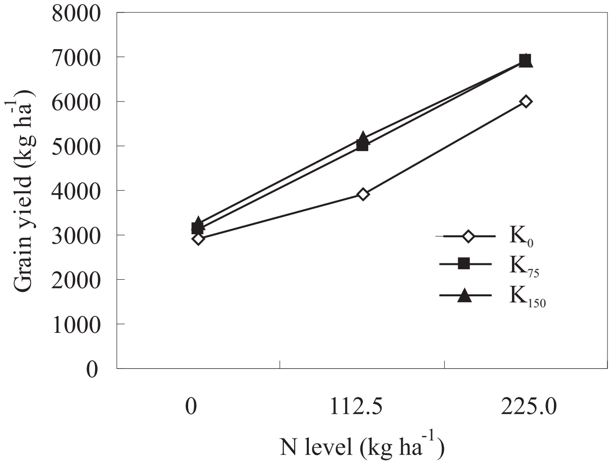

Fig. 4 Effects of K fertilization on wheat yield under variable N regimes (adapted from Zou et al. 2006a)

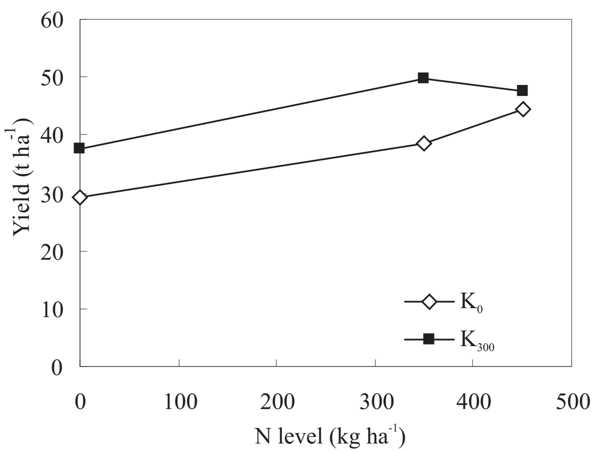

Fig. 5 Effects of K fertilization on cabbage yield under variable N regimes (adapted from Guo et al. 2004)

Intra- and inter-specific differences in response to K application exist in agricultural ecosystems (Rengel and Damon 2008). Moreover, crops show genotypic interactions with N and K (Gething 1993; Pettigrew et al 1996; Tsai and Huber 1996). Research on rice-wheat systems has revealed that responses to direct K application were larger for wheat than for rice (Chen and Zhou 1999; Regmi et al. 2002). Wheat yield was more sensitive to K deficiency than maize (Cai and Qin 2006). The effects of N-K interaction on crops would be expected to be greater at higher yield levels, and it is certainly true that the higher yields now commonly obtained must impose a greater strain on soil reserves of K (Gething 1993). Applying increasing rates of K increased the rate of N required for 90% of maximum canola grain yield. Likewise, applying increasing rates of N increased the rate of K required for 90% of the maximum grain yield (Brennan and Bolland 2009). From 2005 to 2007, multi-site field experiments were conducted in North and Northeast China to evaluate the response of staple crops including maize, wheat and soybean to K application in high-yielding cultivation practices, mainly by ameliorating fertilization such as increasing inorganic N and P fertilizer supply and split-application of N fertilizer, and increasing the plant population. The results indicate that the yield responses of maize and soybean to medium K supply were greater in high-yield cultivation practices (HP) than that in current cultivation practices (CP) which resemble farming practice on average. Wheat, however, did not show the same pattern (Table 4).

Wheat yield responses to K application were insensitive at high yield level, which confirms the general observation of lower response to K fertilization in wheat fields in north China. The N-K interaction was related to soil nutrient status, cultivation practices, crop species, yield level etc. When the exchangeable K in the soil is below the critical value, excessive N fertilization becomes much more critical because the nutrient cannot be used efficiently and the N loss becomes much greater. These principles can be used in practice as a guide to best nutrient management in agricultural ecosystems, especially in intensive rotations.

Table 4. Crop yield increments (%) by K application on average in high-yielding cultivation practices (HP) and current cultivation practices (CP)

Crop	K level	CP	HP	Trials number
Maize	K1	8.5	13.7	14
	K2	14.0	15.9	14
Soybean	K1	13.9	18.2	6
	K2	14.4	12.5	6
Wheat	K1	9.0	7.1	5
	K2	15.6	13.6	5

Note: The K1 and K2 rates indicated medium (75-120 kg K_2O ha^{-1}) and overuse K application (150-240 kg K_2O ha^{-1}) respectively. Specific K levels were decided by executive partners based on specific target crop and experimental sites conditions.

Conclusions

The issue of sustainable management of soil K has partly been ignored during recent decades when the potential environmental impact from agricultural use of nitrogen and phosphorus has been considered to be a more important problem (Simonsson et al. 2007). The yield response to K uptake depends to a great extent on the N supply and the interaction is usually positive. Nitrogen application rate, timing of application and the form of N supplied influence soil K fixation and release as well as K uptake, transport, cycling and reutilization within crops. Optimal N and K favors crop yield and quality as well as stress resistance. Application of N and K in excess of crop demand does not lead to increases in yield and may even cause a yield reduction.

Nitrogen-potassium interactions depend on the form of N supply (nitrate, ammonium or both) and the K and N nutritional levels. Antagonism between NH_4^+ and K^+ was always attributed to simple competitive effects due to competition for binding sites of the respective carriers for their similar charges and hydrated diameters in the past while there was evidence of mixed-noncompetitive interactions. Two distinct membrane transport systems for K uptake by plants, HATS and LATS, have been described. NH_4^+ inhibited HATS which operates primarily at low external concentrations (<1mM) of K^+, while LATS, which dominates at higher external concentration, is relatively NH_4^+ insensitive. The flow and partitioning of K occurring within plants at high mobility can be modified by the form of N supply. NH_4^+ nutrition results in more K being translocated to leaves than occurs with NO_3^- supply. This result suggests that good quality of tobacco with high K concentration can be obtained by combined application of NH_4^+-N with other N forms. Nitrogen-potassium interactions have been significant in numerous studies and are complicated. The N-K interaction has been related to soil nutrient status, cultivation practices, crop species, yield level and the forms of N supplied.

In many intensive agricultural production areas, large amounts of N are supplied in order to achieve higher crop yields and this has led to low N use efficiency and serious environmental problems. At present, nitrogen use efficiency on staple crops such as rice, wheat and maize in China in terms of recovery N efficiency (RE_N) is 27.5% on average (Zhang et al. 2007). Balancing the NPK ratio by increasing the input of K-fertilizers is a practical way to improve N agronomic efficiency (Zhu and Chen 2002). If optimum N is applied to plants in the presence of suitable K level, plant productivity increases which could be due to increase in N use efficiency of the plants.

It appears that K application can alleviate the N pollution problem by inducing a high uptake rate of N by crops (Ardjasa et al. 2002; Yang et al. 2006). The positive interaction of N and K may offer the opportunity for considerable savings in the cost of N fertilizer and food security for the rapidly expanding human population. Therefore, N and K fertilizers should be applied with optimal ratios at the right time and right rate according to the nutrient uptake pattern of the crops, soil nutrient status, soil texture and climate changes, in order to reach the target yields with good quality and minimize K and N losses to the environment. A good understanding of the mechanisms of N-K interactions may serve as a guide to best nutrient management practice in agriculture. Further studies on N-K interaction on yield responses, stress resistence, gentypic difference of different crops, and the mechanims on molecular level should be continued as well as the adverse impacts to environment.

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Mineral nutrition under salt stress

Anil Kumar Singh • Ali Qadar • NPS Yaduvanshi

Abstract Salt-affected (salinity as well as sodicity) soils cover an area of about 831 m ha (> 6 percent of the total ice-free land in the world). About 6.74 million ha area is affected with salinity and sodicity in India. In addition to osmotic stresses, plants growing in these soils are exposed to a number of unfavourable conditions like moisture stress, elemental toxicity, poor soil physical conditions, and imbalance and deficiency of nutrients. Plant responses to these adverse conditions are complex and their nutrient requirement may not be same as it is under non-stress conditions. The relation between salt stress and mineral nutrition of plants is complex as the activity of nutrient elements is altered because of excess of potentially toxic ions and antagonistic effects on uptake of each other and pH induced changes in their solubility and availability. Nitrogen is the most limiting nutrient in these soils because of low inherent fertility and organic matter, poor symbiotic N fixation and higher volatilization losses leading to low efficiency of applied fertilizer-N. Evidence exists which supports that nutrient levels considered optimal in non–salt stress conditions may be inadequate under salt stress and 25 percent more N should be applied. Olsen's P in these soils particularly under sodicity is very high, thus P should not be applied in the initial 3-5 years of reclamation. Salt stress reduces uptake of P and its accumulation mainly by reducing its absorption especially under saline conditions. The reduction in P absorption is attributed to antagonistic effects of Cl^-. Addition of P (within a certain range) in several studies not only helped plants in terms of growth and yield, but also improved the tissue tolerance. Excess of Na and Cl in the medium reduces uptake of K and NO_3, respectively. Na induced K deficiency is reported and under that situation, addition of K is likely to be beneficial for growth and yield. Those crops especially the horticultural crops, which are highly sensitive to Cl toxicity, are likely to be benefitted by adding more N as NO_3 to offset the effects of Cl on its uptake. In general, SO_4 salinity of the same EC as that of Cl is less toxic compared to Cl dominated salinity.

Excess of Na not only reduces Ca availability, its transport and mobility to growing regions of the plants, but also impairs the integrity of cell membrane

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leading to uncontrolled influx and efflux of several elements. Alkali soils contain low amounts of DTPA extractable Zn. Due to high pH, ESP, calcium carbonate and low amounts of organic matter, efficiency of applied Zn fertilizer is much less and the crops, especially rice, suffer from Zn deficiency. Low efficiency of applied fertilizers in salt affected soils is due to low uptake of the nutrients because of antagonistic effects on each other and their impaired utilization and higher losses of nutrients during the leaching of the salts.

Keywords Crop management • inland salinity • salt-affected soils

Introduction

Salt affected soils are found in more than 100 countries and it is estimated that approximately 831 million hectares (mha) are affected world wide, which account for more than 6percent of the world's total area (Martinez-Beltran and Manzur 2005). Out of these, 397 mha are saline and 434 mha are sodic. More areas are going out of cultivation where irrigation is not applied judiciously, and specifically when irrigation water is saline. Of the current 275 mha of irrigated land about 20 percent (55 mha) is salt affected, which might be up to even 50 percent (Pitman and Lauchli 2004; FAO, 2005). Of the 1,500 mha of dryland agriculture, 32 mha are salt affected to varying degrees (Ghassemi et al. 1995; FAO 2008). Secondary salinisation of agricultural land is widespread, particularly in arid and semiarid environments where irrigation is unavoidable to achieve good production. At the current level of food supply, the food production needs an increase of 38 percent by 2025 and 57 percent by 2050 to meet the demand of growing population (Wild 2003). The area affected by salinity and sodicity in India is about 6.73 mha (2.96 mha saline and 3.77 mha sodic), and distributed in 15 states (Table 1) (NRSA and Associates 1996). Salt affected soils are spread over the Indo-Gangetic plains, arid regions and coastal areas. With the expansion of irrigation, vast acreage of non-saline soils in the canal command areas have been affected by secondary salinity. Salt affected soils affect agricultural production as virtually all crops are adversely affected. There are considerable variations among the different crops and their cultivars to tolerate salt stress (Gupta and Abrol 1990; Francoise and Mass 1994; Qadar 1995).

In addition to its toxicity, Na^+ also interferes with the uptake of other essential nutrients like K and Ca. Also high concentration of Na^+ reduces the activity of many nutrients. In contrast to non-saline conditions, salt affected soils have high concentrations of Na and Cl ions, which may depress nutrient ion activities and cause extreme ion ratios of $Na^+ : Ca^{2+}$, $Na^+ : K^+$, $Ca^{2+} : Mg^{2+}$, $Cl^- : NO_3^-$, $Cl^- : H_2PO4^-$. The extreme ratios are likely to cause nutritional disorders.

Table 1 State wise distribution of salt affected soils in India (ha)

State	Saline Soils	Sodic Soils	Total
Andhra Pradesh	77598	196609	274207
Andaman & Nicobar Isalnds	77000	0	77000
Bihar	47301	105852	153153
Gujarat	1680570	541430	2222000
Haryana	49157	183399	232556
Karnataka	1893	148136	150029
Kerala	20000	0	20000
Madhya Pradesh	0	139720	139720
Maharashtra	184089	422670	606759
Orissa	147138	0	147138
Punjab	0	151717	151717
Rajasthan	195571	179371	374942
Tamil Nadu	13231	354784	368015
Uttar Pradesh	21989	1346971	1368960
West Bengal	441272	0	441272
Total	2956809	3770659	6727468

Source : NRSA and Associates 1996

Nitrogen

In one or other form, nitrogen (N) accounts for about 80 percent of the total nutrients absorbed by the plants (Marschner 1995). Salt stress soils are very low in organic matter and available N throughout the soil profile. Because of this, most crops suffer from inadequate N supply. Nitrogen transformations are adversely affected by high pH and sodicity/salinity. High soil pH coupled with poor physical conditions also adversely affects the transformations and availability of applied nitrogenous fertilizers. Martin et al. (1942) reported that threshold pH value for nitrification of ammonia was 7.1±0.1. They observed that nitrification did occur at higher pH values but was accompanied by considerable accumulation of nitrites. NH_3 volatilization can be a pathway through which N is lost from soil-plant system after the application of nitrogen fertilizers. Ammonium fertilizers are particularly subjected to volatilization losses if they remain on the surface of a damp but drying calcareous soil and the fertilizer anion forms an insoluble calcium salt.

Increase in volatilization losses of NH_3 was noticed with a decrease in solubility of reaction products of NH_4^+-N sources with Ca compounds. Jewitt (1942) observed a loss of 87 percent N from ammonium sulphate applied to a Barber soil (pH 10.5) in northern Sudan. Similarly, Bhardwaj and Abrol (1978) observed that 32 to 52 percent of the applied nitrogen was lost through volatilization in alkali soils. Laboratory and field studies have shown lower losses of N from green manuring as compared to urea - N (Rao and Batra 1983; Yaduvanshi 2001a). The loss N as NH_3 volatilization from green manuring combined with urea, was 13.4 percent as compared to urea application (19.5%) alone (Table 2).

Table 2 Ammonia losses from reclaimed sodic soil rice field in integrated nutrient management system

Treatment combination	Urea application			Total N lost	Urea N lost (%)	pH
	1st	2nd	3rd			
Control	1.25	-	-	-	-	8.56
N_{120}	8.49	8.21	6.76	23.46	19.55	8.49
$N_{120}P_{22}$	8.28	7.35	6.70	22.33	18.61	8.48
$N_{120}P_{22}K_{42}$	8.14	7.24	6.65	21.75	18.13	8.45
$N_{120}P_{22}K_{42}$	5.82	5.20	5.06	16.08	13.40	8.10
$N_{120}P_{22}K_{42}$	6.73	5.74	5.28	17.75	14.79	8.15
$N_{180}P_{39}K_{63}$	12.12	10.60	9.48	32.20	17.89	8.49
Mean	8.26	7.39	6.66			
CD (P=0.05)	0.51	0.91	1.19			
Stage of Urea application	0.32					

Source: Yaduvanshi 2001a

Symbiotic nitrogen fixation in salt-affected soils

Bhardwaj (1975) reported that though Rhizobia could survive in sodic soils of pH as high as 10.0, the effective contribution of the bacteria to the plant's needs of N was limited because of delayed nodulation and the sensitivity of the host plants to soil sodicity. In general, it is recommended that 25 percent more N should be applied in salt affected soils. Ammonium sulphate proved to be better source of N for rice and wheat in terms of grain yield, as compared to urea and calcium ammonium nitrate (Nitant and Dargan 1974). This was attributed to the beneficial effect of residual acidity of this fertilizer.

To get the maximum advantage, N application should synchronize with the growth stage at which plants have the maximum requirement for this nutrient. Split application of N for wheat (½ at sowing, remaining ½ N in two splits at tillering (21 days) and 42 days after sowing and for rice (half at transplanting + ¼ at tillering + ¼ at panicle initiation) resulted in maximum efficiency (Dargan and Gaul 1974). Foliar application of N (3% solution of urea) together with a basal application gave good results and saved 40 to 60 kg N ha^{-1} in alkali soils (Swarup 1994; Yaduvanshi 2001b). The crop yield is higher when both chemical and organic sources are used as compared to either chemical or organic sources individually. This is attributed to the proper nutrient supply as well as creation of better soil physical and biological conditions when the two are combined together. Addition of N in N deficient soils at moderate salt stress level, improved growth and/or yield of crops, however, there is no information for field condition where an increase in crop yield is noted under salt stress at higher level of N than considered optimum for non-salt stress condition.

Chloride salts are reported to depress nitrification whereas low concentrations of SO_4^{2-} promoted it (Agarwal et al. 1971). Westerman and Tucker (1974) observed that high concentration of salts (KCl and K_2SO_4) inhibited nitrification and caused NH_4^+-N accumulation. Salinity did not affect the hydrolysis of urea, but nitrification was severely inhibited (McClang and Frankenberger 1985). Hence, plants that absorb N preferably as NO_3^- are likely to show a deficiency of N even though it may be present in the soil. Under such situations, additional N application may not improve the crop growth and yield. Reduction in N accumulation is understandable as Cl^- (saline condition) and NO_3^- (present in soil) have antagonistic effects on uptake of each other. This was observed in cucumber (Martinez and Cerda 1989), eggplant (Savvas and Lenz 1996); melon (Feigin et al., 1987), and tomato (Kafkafi et al. 1982; Feigin et al. 1987). Salinity induced reduction in NO_3^- concentration in wheat leaves is reported without affecting the total nitrogen content and addition of NO_3^- resulted in reduction in Cl^- uptake (Hu and Schmidhalter 1998). Accompanying cations also influenced reduction in NO_3^- uptake by Cl^-. The effects of Cl^- from NaCl and KCl on inhibition of NO_3^- uptake were similar but that from $CaCl_2$ were more pronounced at the lower salinity range (Kafkafi et al. 1992). They found that Cl^- from $CaCl_2$ and not KCl, inhibited NO_3^- uptake in melon and tomato in a range to which the plants are likely be exposed in field conditions (i.e. up to 60 mol m^{-1}). It was only in the high concentration range (100-200 mol m^{-1}) that KCl inhibited NO_3^- uptake.

Plants, especially fruits and vines, which are sensitive to Cl^- are likely to be benefited with NO_3^- fertilization (Grattan and Grieve 1999). Study on avocado and citrus (both sensitive to Cl^-) showed that increasing NO_3^- in the media, which was otherwise sufficient for growth under non-salt stress condition, decreased Cl^- concentrations in their leaves with reduction in foliage symptoms of Cl toxicity and improvement in growth (Brar et al. 1997). The concentration of NO_3^- effective in reducing Cl^- concentration in plant has to be high (molar ratio of NO_3/Cl, 0.5 and above) in soil solution. Martinez and Cerda (1989) also reported reduction in Cl^- uptake in cucumber when only NO_3^- was added to the solution but when half the NO_3^- in the solution was replaced by NH_4, Cl accumulation was enhanced. NH_4-fed maize (Lewis et al. 1989), melon (Feigin 1990) and pea (Speer et al. 1994) plants showed higher sensitivity to salinity than NO_3-fed plants when grown in solution cultures. Specific cations like Ca have also been reported to play a role, e.g., addition of Ca to the media improved the growth rate of the plants in the NO_3 treatment, but not those treated with NH_4 (Lewis et al. 1989). In presence of NO_3 as the only source of N, K uptake increased in salt-stressed melon and with increase in NH_4/NO_3 ratio, the accumulation of Cl^- increased, but the reverse was true for Ca and K in the leaves (Adler and Wilcox 1995). Crop responses may not be the same for the same source of N in different growing conditions. Leidi et al. (1991) and Silberbush and Lips (1991a, b) reported higher sensitivity of wheat (Triticum aestivum L.) to salinity as the ratio of NH_4/NO_3 increased in solution and sand culture. Contrary to this, wheat grown in soil salinised with NaCl, showed improved salt tolerance in terms of grain yield under a combination of NH_4 and NO_3, than NO_3 alone (Shaviv et al. 1990)

Phosphorus

The plant roots largely absorb it as dihydrogen orthophosphate ion ($H_2PO_4^-$), however, under neutral to alkaline environments, it is also taken up as monohydrogen orthophosphate (HPO_4^{2-}) ion. The high amounts of Na_2CO_3 and Na_2HCO_3 react with native insoluble calcium phosphates to form soluble sodium phosphate and hence, give a positive correlation between the electrical conductivity and their soluble P status. Due to high pH and the presence of soluble carbonates and bicarbonates, water soluble sodium phosphates are formed in these soils. Sodic soils are reported to contain high amount of soluble phosphorus. Research conducted at CSSRI revealed lack of response to added phosphorus in sodic soils during early years after reclamation. However, other studies, indicated that sodic soils are not always high in available phosphorus and significant increase in yields of some crops was obtained with application of P fertilizer**.** When these soils were reclaimed by using amendments and growing rice under submerged conditions, Olsen's extractable P of surface soil decreased due to its movement to lower sub-soil layers, uptake by the crop and increased immobilization (Chhabra et al. 1981; Swarup 1986; 1994). In freshly reclaimed alkali soils, crops did not respond to application of phosphatic fertilizers in the initial 3 to 5 years. During this period, continuous cultivation also improved the soils considerably in the upper 15-cm (pH_2 8.5-9.0). It was observed that if the Olsen's P of the surface 15-cm soil falls below 7.5 kg P ha^{-1}, rice yields may suffer. Nutrient uptake in rice (a shallow–rooted crop) is dependent on the fertility status of the surface 30-cm layer, which becomes depleted and start responding to P fertilization. On the other hand, wheat plants, with a relatively deeper rooting

system, can extract P from the lower layers to meet their needs, therefore, do not respond to applied P for another 3 to 5 years. Long-term field studies were conducted on a gypsum amended alkali soil (pH_2 9.2, ESP 32) with rice wheat and pearl millet cropping sequence and NPK fertilizer use for 25 years (1974-75 to 1999-2000). Phosphorus application enhanced the grain yield of rice (Yaduvanshi 2003) when Olsen's extractable P in 0-15 cm soil depth had reduced from the initial level of 33.6 kg ha^{-1} to 12.7 kg ha^{-1}, and wheat responded to applied P when available P came down close to 8.7 kg P ha^{-1}. Crop responses to applied P were limited to the application of 11 kg P ha^{-1} in the initial years of cropping and that too only to rice crop in a rice-wheat cropping sequence. Subsequently, application of 22 kg P ha^{-1} significantly improved the rice and wheat yield. Recent studies on integrated nutrient management showed that continuous use of fertilizer P, green manuring and FYM to crops significantly enhanced the yield of rice and wheat as well as improved the available P status of the alkali soils (Yaduvanshi 2000).

The available P status of saline soils is highly variable and does not show any trend or relation to level of soil salinity. The availability of fertilizer phosphorus in the soil may be modified by soil salinity due to higher precipitation of added soluble P (Taylor and Gurney 1965), higher retention of added P by the soil (El Mahi and Mustafa 1980) and due to antagonistic effect of excess Cl on the P sorption by the plants (Manchanda and Sharma 1983). Wheat responded significantly to P application up to 50 kg ha^{-1} (0, 25, 50 and 75 kg ha^{-1}) in terms of grain yield at the site irrigated with Cl^- dominated water (EC 15-19 dS m^{-1}), but there was no response to applied P on the $SO_4^{=}$ irrigation water site although the former (irrigated with Cl^- dominant water) had more Olsen's P than the latter (Manchanda et al. (1982). Barley crop irrigated with Cl^- dominant water also showed higher requirement of P. It has been generally observed that application of P fertilizers increased crop yields in saline soils (Singh et al. 1990, 1992). Higher plant responses to applied phosphorus occurred on moderately saline soils than on non-saline soils. Manchanda and Singh (1982) and Manchanda and Sharma (1983) reported that P requirement under SO_4^- dominated saline conditions (SO_4> 70%) was either less or at the most equal to the non-saline soil, whereas in case of under Cl -dominated salinity (Cl > 70%), it was considerably more than that of the non-saline soil. Application of P helped rice plants to restrict increase of Na^+ concentration under salinity (Naheed et al. 2008). Rice genotypes showed higher requirement of P with increase in sodicity stress (Qadar 1998). Seedlings of CSR13 and Jaya (moderately tolerant to sodicity) did not show any problem of survival and growth at pH_2 8.0, with Olsen's-P 8.5 kg ha^{-1} but failed to survive at pH_2 9.7 and 9.9 where Olsen's-P was 12.5 and 14.8 kg ha^{-1}, respectively. However, there was no problem of survival or growth at these sodicity levels when Olsen's-P was raised to 17.6 and 20.8 kg ha^{-1}, respectively, and plants attained maturity and produced grain (Table 3). CSR10, a sodicity tolerant genotype showed less response to added P. Plants fertilized with P had less Na^+, a potentially toxic ion in the shoot. It is likely that internal plant requirement of P is higher under stress for restricting uptake of Na^+ at root level and its better regulation at tissues/cellular

Table 3 Grain yield (g pot^{-1}) of three rice genotypes as influenced by fertilization of sodic soils with P and alone or in combination

Treatment kg ha^{-1}	Genotype	pH_2 8.0	9.3	9.7	9.9
K_0P_0	CSR 10	44.9	28.1	19.7	14.0
	CSR 13	59.0	23.7	0.0*	0.0*
	Jaya	46.7	22.1	0.0*	0.0*
$K_{60}P_0$	CSR 10	44.6	33.3	21.7	15.7
	CSR 13	56.6	23.2	0.0*	0.0*
	Jaya	50.5	22.1	0.0*	0.0*
K_0P_{60}	CSR 10	55.9	42.4	34.9	25.0
	CSR 13	60.0	50.5	34.5	19.6
	Jaya	60.2	47.1	38.4	18.5
$K_{60}P_{60}$	CSR 10	54.7	42.2	33.9	26.3
	CSR 13	60.3	46.3	36.1	18.3
	Jaya	60.9	47.6	37.4	25.4
CD (P=0.01)	Fertilizer (F)	2.2	FxS 4.4	FxGxS	7.6
	Sodicity (S)	2.2	FxG 3.8		
	Genotype (G)	1.9	GxS 3.8		

* Plants failed to reach maturity, Source: Qadar 1998

Table 4 Total chlorophyll/100 mg kg^{-1} Na load in top three leaves of rice at pH_2 9.7 in response to phosphorus and potassium fertilization

Leaf	Phosphorus fertilization P_0	P_{20}	P_{40}	P_{60}	P_{80}	Mean
Flag leaf	2.95	3.80	4.57	4.26	4.71	4.06
Next lower leaf	3.12	3.12	4.57	4.22	4.00	3.67
3rd lower leaf	1.58	1.98	2.81	3.11	3.25	2.55
Mean	2.55	2.97	3.87	3.80	3.95	
CD (P=0.01)	Leaf (L) 0.25, Phosphorus levels (P) 0.32					
CD (P=0.05)	LxP 0.47					

Source: Qadar and Ansari 2006

levels (sequestering in the vacuole). This is reflected with higher chlorophyll contents in the leaves of P fertilized plants in sodic soil (Table 4) (Qadar and Ansari 2006).

Phosphate availability to plants is likely to be reduced in saline soils because of its reduced activity as a result of increased ionic strength and because phosphate concentrations in soil solution are tightly controlled by sorption processes and by the low-solubility of Ca-P minerals

Potassium

Most of the plants invariably show a decrease in K concentration under salt stress and maintenance of adequate levels of K is essential for plant survival in saline habitats (Marschner 1995). High Na^+ level in the ambient solution surrounding the roots may disrupt the integrity of root membranes, thus, compromising on their selectivity. Plants absorb potassium as potassium ions (K^+). In general, increasing soil ESP decreases the K and increases the Na content of the plants. Numerous studies have shown that K concentration in plant tissues declines with increase in the levels of salt stress or Na/Ca in the root media leading to high Na/K ratio (Subbarao et al. 1990; Izzo et al. 1991; Qadar 1991; Perez-Alfocea et al. 1996). Contrary to these observations, an increase in K levels of the cell sap of bean leaves were found to be associated with increasing NaCl salinity (Cachorro et al. 1993). Due to high Na and deficiency of Ca, many studies have shown reduced uptake of K by plants raised in alkali soils (Singh et al. 1981). The antagonistic effect of Na^+ on uptake of K^+ occurs both under sodicity (CO_3^{2-}, HCO_3^- predominant anions) and salinity where Cl^- and SO_4^{2-} are predominant anions (More and Manchanda 1992; Qadar and Azam 2007). Chickpea and pea shoots grown in the SO_4^{2-} system contained more K than in the Cl^- system (Manchanda and Sharma 1989; More and Manchanda 1992). However, absolute K concentration in the plant tissue is nearly always above the lower critical limit. Alkali soils in the lndo-Gangetic plains generally contain very high amounts of available K (Swarup and Chhilla, 1986). Application of K fertilizer to either or both the crops had no effect on yields of rice and wheat (Swarup and Yaduvanshi 2000). The contribution of the non-exchangeable K towards total potassium removal was about 94.9 percent in the absence of applied K, which decreased to 69.9 percent with use of K. The decrease was about 50.6 percent with use of K combined with organic manures (Yaduvanshi 2000). Chhabra (1985) reported that to correct lower content of K in the plants raised on K rich alkali soils, add recommended doses of amendments to correct Ca:Na:K balance rather than apply K fertilizers.

Significant leaching losses of K (3.2 to 8.2 mg K L^{-1}) in the drain water effluents (Swarup 1995), and higher levels of available K into the lower soil depths indicated continuous movement of native and applied K from the surface to the lower layers and even beyond the effective root zone causing deficiency of available K in surface layer of saline soils under sub surface drainage system. Sodium toxicity may be more common in saline soils than in alkali soils. Wheat responded to K up to 90 kg K_2O ha^{-1} in saline sodic (ECe 5.31 dS m^{-1}, pHs 8.56) under field conditions both in terms of growth and yield, which had 118 mg L^{-1} extractable K (Mehdi et al. 2007). Very limited information is available on added K in alleviating the adverse effects of salt stress on crops under field conditions.

Sulphur

Sulphur is a secondary nutrient, but in most of the studies where response of crops to SO_4^{2-} and Cl^- dominated salinities were examined, nutritional aspect of sulphur was often overlooked. Not much attention has been given to the influence of salinity on the uptake of sulphur and its accumulation in crops. More and Manchanda (1992) compared the effects of both chloride and sulphate salinity on pea and reported that chloride-salinity reduced the sulphur content in the straw. Sulphur accumulation in the roots, however, was enhanced by Cl-salinity. Crops sensitive to Cl^- dominated salinity are invariably unable to tolerate high Cl^- concentrations at cellular level, and when compared to their response to Cl-salinity and SO_4- salinity showed better tolerance to the latter condition. This has led to the suggestion that for most of the vegetable crops salt-tolerance would be 2 dS m^{-1} greater in a sulphate system as opposed to chloride system (Bernstein 1962).

Calcium

Plants absorb calcium as Ca^{2+} ions. It is most abundant in plant available forms in the soil. It is important for the growth of meristems and functioning of the root tips. Besides being structural component of the cell, Ca plays a vital role in regulating many physiological processes that influence both growth and development and also responses to abiotic stresses including salt stress. Its importance in maintaining the structural and functional integrity of cell membrane, stomatal function, cell division, cell wall synthesis, translocation, direct or signaling roles in systems involved in plant defense, repair from biotic and abiotic stress and rates of respiratory metabolism are well known (Marschner 1995; McLaughlin and Wimmer 1999). Cachorro et al. (1994) reported that addition of calcium to the saline media increased root membrane integrity of bean and minimized leakage of NO_3 and H_2PO_4. The alkali soils are deficient in both soluble and exchangeable Ca, and excess of soluble and exchangeable Na further aggravates its availability to plants. Mehrotra and Das (1973) reported that crops which have a narrower Ca:Na ratio under normal soil conditions are relatively more tolerant to alkalinity than those that have a broader ratio. Under high levels of salt stress, Ca^{2+} uptake and transport to all organs is significantly reduced. As Na^+ readily displaces Ca^{2+} from its extracellular binding sites, Ca^{2+} could be seriously reduced especially at low Ca^{2+}:Na^+ ratio (Cramer et al. 1988). Addition of Ca^{2+} alleviated the adverse effects of NaCl stress on bean plants (LaHaye and Epstein 1971). Bean plants subjected to a NaCl concentration about one tenth that of seawater for one week suffered no damage if the Ca^{2+} concentration of the nutrient solution was 1 mmol L^{-1} or higher. But at lower calcium concentrations the damage was severe and apparently due to a massive breakthrough of Na^+ into the leaves. Low Ca^{2+}:Na^+ ratio in the media also causes significant morphological and anatomical changes and Ca^{2+} deficiency in general, can impair the selectivity and integrity of cell membrane causing passive accumulation of Na^+ in plant (Cramer and Nowak 1992). Elevated external Ca^{2+} also inhibits Na^+-induced K^+ efflux through outwardly directed, K^+-permeable channels. NaCl-induced K^+ efflux was partially inhibited by 1 mmol Ca^{2+} and fully prevented by 10 mmol Ca^{2+} (Shabala et al. 2006). Calcium was found to be effective at reducing the transport of both Na^+ and Cl^- from roots to leaves in citrus grown under saline conditions, thereby, alleviating foliar injury and/or defoliation (Banuls et al. 1991; Zekri and Parsons 1992; Zekri 1993; Banuls et al. 1997). Calcium appeared to offset damage to blueberry shoots salinized with Na_2SO_4, but not with NaCl (Wright et al. 1992; 1993; 1994). Salinity (NaCl) adversely affected water transport properties of maize primary roots by NaCl-induced morphological and anatomical changes (Evlagon et al. 1990; Neumann et al. 1994). Added Ca^{2+} tended to reverse or prevent these changes and mitigated reductions in root hydraulic conductivity (Azaizeh and Steudle 1991; Azaizeh et al. 1992; Neumann et al. 1994). Amendments like gypsum, phospho-gypsum and press-mud are most commonly used. Since all alkali soils are calcareous in nature, use of acids like H_2SO4, or acid forming materials like pyrites (FeS_2) and elemental S are also helpful in solublising the native $CaCO_3$ and thus meet the Ca needs of plant and soil. The availability of Ca from applied $CaSO_4$ depends upon the soil ESP, root CEC, and plant species. Poonia and Bhumbla (1972) using ^{45}Ca reported that 31 percent of Ca in Sesbania aculeata (high root CEC) was contributed by the added $CaSO_4$, while in Zea mays (low root CEC) it was only 17 percent. Addition of organic matter in the form of FYM, press-mud, poultry manure, paddy and wheat straw, and green manure through Sesbania all help in solublising native $CaCO_3$ and thus improve the soil. Decomposition of organic matter under anaerobic conditions helps in increasing pCO_2 and production of acids and acidic products, which increase the solubility of native $CaCO_3$. Addition of amendments is a pre-requisite for getting good stand of the crop, reduce toxicity of Na, and meet Ca needs of plants.

Sodium

Sodium is a predominant cation both in saline and sodic soils. It is considered to be non-essential in plant system and its excess uptake creates problem of Na toxicity. One of the best strategies is to restrict its uptake when plants are growing in saline sodic soils. Its sequestration in the vacuoles not only avoids its interference with the normal metabolic activity leading to its toxicity but also serves as a beneficial osmolyte. Nevertheless, sodium is the principal electrolyte in the plant system. Many halophytic plants can utilize Na under conditions of limited availability for non-K specific functions (Subbarao et al. 1999, 2000). Glycophytic plants such as beets, celery, turnip and spinach, which are natrophilic in nature could be better suited for cultivation in salt affected soils. Many C_4 plants species like Atriplex vesicaria, A. tricolour, A. amnicola, Kochia childsii and Panicum miliaceum require Na for optimum growth (Qadar 1992; Marschner 1995). However, other C_4 species like sorghum, maize, and sugarcane do not show such a response to Na (Ohnishi et al. 1990)

Zinc

Solubility of micronutrients like Zn, Fe, Mn, Cu and Mo in saline and sodic soils is low and plants often experience deficiencies of these elements (Page et al. 1990). There is a 100-fold decrease in solubility of Zn per unit increase in pH (Lindsay 1972). The availability of most of the micronutrients to plants depends on pH and pE (negative logarithm of the activity of electron). Plants absorb zinc as Zn^{2+}. Most of the alkali soils contain high amount of total Zn (40 to 100 mg Zn kg^{-1} soil) and most of this is in an insoluble form and its solubility is influenced by pH and presence of $CaCO_3$. Generally, sodic soils contain less than 0.6 mg DTPA–extractable Zn kg^{-1} soil (Singh et al. 1984). A negative correlation was observed between extractable Zn and pH as well as $CaCO_3$ content of the soil (Mishra and Pandey 1976). The solubility of Zn in alkali soils is dependent by the solubility of $Zn(OH)_2$ and $ZnCO_3$, which are the immediate reaction products (Dhillon et al. 1975). The higher Zn extractability at high ESP was attributed to the formation of sodium zincate, which is soluble. On addition of amendments, the extractability of added Zn decreased (Singh et al. 1984) due to greater adsorption of Zn by Ca-than by Na saturated soil, retention of added Zn on the surface of freshly precipitated $CaCO_3$ formed as a result of reaction between soluble carbonates and added gypsum, and enhanced competition of added Ca with Zn for the DTPA ligands during extraction. Shukla et al. (1980) observed that Zn adsorption in soils saturated with various cations was of the order of H < Ca < Mg < K < Na.

Efficiency of applied fertilizer Zn depends upon the degree of amelioration

brought about in the alkali soils. When the recommended doses of amendments are added to the soil, 10 to 20 kg $ZnSO_4$ ha^{-1} is enough to get optimum yields of crops. At low level of gypsum application, the plants suffer more due to excess of Na and deficiency of Ca and become incapable of utilizing absorbed Zn. As a result, the crop suffers and results in poor yields (Singh et al. 1987). It has been observed that on soils containing $\geqq$ 1 mg kg^{-1} of DTPA-extractable Zn, it is enough to apply Zn only to rice crop in the rice-wheat cropping sequence (Chhabra et al. 1976). Best results are obtained when $ZnSO_4$ is added along with other fertilizers as a basal dose. With the application of FYM and Sesbania green manure, it was possible to prevent the occurrence of Zn deficiency in rice grown on alkali soils (Sawrup 1991). Organic amendments like pressmud, poultry manure and farmyard manure could effectively supply zinc from the native and applied sources to rice crop in a saline sodic soil (Milap Chand et al. 1980). Zinc applications improved growth of salt-stressed tomato plants (El-Sherif et al. 1990).

Iron

Solubility of Fe in saline and sodic soils is low and plants often suffer deficiency of this element in salt affected soils (Page et al. 1990). The alkali soils are rich in total Fe but are generally poor in water-soluble plus exchangeable and reducible forms of Fe (Swarup 1989). There exists a negative relationship between pH and Fe-Mn availability. Soluble Fe-salts when applied to alkali soils are rendered unavailable because of rapid oxidation and precipitation, consequently their recovery by soil-test methods is very low (Swarup 1981). Since iron solubility is conditioned by pH, $CaCO_3$, oxidation status of the soil and the amount of organic matter, it is not the total-Fe but the available-Fe that is a limiting factor in alkali soils. Correction of iron deficiency using soluble salts as $FeSO_4$ is generally not effective unless it is accompanied by changes in the oxidation status of the soil brought about by prolonged submergence and addition of easily decomposable organic matter (Katyal and Sharma 1980). Foliar application of Fe (3% solution of $FeSO_4$) gave a limited relief to the suffering crop and must be used to supplement the improvement in reduction status of the soil. Results available on Fe concentration in plants growing under salt stress are as inconsistent as those for Zn concentration. The concentration of Fe in the shoots of pea (Dahiya and Singh 1976), tomato, soybean (Glycine max (L.)), squash (Maas et al. 1972) and lowland-rice (Verma and Neue 1984) increased, but its concentration decreased in the shoots of barley and corn under salinity (Hassan et al. 1970a; b). Iron nutrition does not seem to be a problem in paddy in sodic soils as anaerobic conditions favour reduction of Fe^{3+} to Fe^{2+} form. However, considerable variations existed among the genotypes in their Fe concentrations in the shoot (Qadar 2002).

Manganese

The solubility and availability of Mn in soil is also affected by pH and oxidation-reduction status of the soil. The alkali soils are rich in total Mn but are generally poor in water-soluble plus exchangeable and reducible forms of Mn (Swarup 1989). Deficiency of Mn is seldom a problem for wetland rice, while it can become a serious limiting factor for subsequent crops like wheat, because on submergence Mn gets reduced and is leached to the lower layers (Chhabra 1996). As a result, Mn deficiency is increasingly being observed in wheat grown in rice-wheat cropping system on coarse textured alkali soils. Due to oxidation of Mn, it is very difficult to correct Mn deficiency by soil application of $MnSO_4$ and repeated spray of $MnSO_4$ is needed to make up the deficiency of this element in upland crops. Adoption of rice-wheat system for more than two decades on gypsum-amended alkali soils resulted in decline of the DTPA- extractable Mn to a level of 2.7 mg kg^{-1} and in those conditions wheat responded to $MnSO_4$ application at a rate of 50 to 100 kg ha^{-1} (Soni et al. 1996). Substantial leaching losses of Mn occurs following gypsum application in alkali soils (Sharma and Yadav 1986). In a study with rice genotypes for their tolerance to sodicity and Zn deficiency stresses, an increase in Mn concentration was found under sodic conditions (Qadar 2002).

Salinity-induced Mn deficiency is reported in barley (Hordeum vulgare L.) shoots and Mn additions to solution cultures increased its salt-tolerance (Cramer and Nowak 1992). Salinity caused reduction in Mn concentration in shoot tissues of corn (Izzo et al. 1991; Rahman et al. 1993) and tomato (Alam et al. 1989). Contrary to these, Mn concentration in sugarbeet shoot increased with salinity (Khattak and Jarrell 1989) which is probably because of increased plant available Mn in saturated soil as a result of added salt (NaCl, $CaCl_2$). Manganese and Zn concentrations also increased in rice (Verma and Neue 1984) under salinity stress, but decreased in corn (Hassan et al. 1970b).

Boron

Boron is considered to be absorbed passively as H_3BO_3. Its toxicity rather than deficiency is expected in sodic soils as its availability increases with increase in soil pH and ESP. Kanwar and Singh (1961) observed a positive correlation between water-soluble B and pH as well as EC of soils. Uncultivated alkali soils in Haryana and Punjab are reported to have hot water extractable B up to 25 mg kg^{-1} in 0-15 cm (Bhumbla et al. 1980). In addition of leaching, B hazards in alkali soils can be minimized by addition of gypsum. From a laboratory study, Gupta and Chandra (1972) reported a marked reduction in water soluble B together with pH and SAR, on addition of gypsum to a highly alkali soil. At high pH/ESP, boron is present as highly soluble sodium metaborate, which upon addition of gypsum is converted into relatively insoluble calcium metaborate. The solubility of calcium metaborate is very low around 0.4 percent as compared to 26 to 30 percent of sodium metaborate.

Although high boron and high salinity occur in many parts of the world, very little research has been done to study their interactions (Ferreyra et al. 1997) and results are often contradictory. Some research showed increased tolerance of plants to B with increased salinity (Yadav et al. 1989; Holloway and Aston 1992; Grattan et al. 1996; Ferguson et al. 2002). However, decreased tolerance to B in the presence of salinity stress has also been reported (Grieve and Pass 2000; Alpasalan and Gunes 2001; Wimmer et al. 2003, 2005). The differences in results were because of plant/crop types or varieties, composition of salts used for salt stress, environmental conditions and external pH. Mehmood et al. (2009) reported increased growth and yield of rice in saline sodic conditions with B application up to 1.5 kg B ha^{-1} and this beneficial effect was due to reduced concentration of Na^+ and Cl^- in the shoot. Application of 6.0 kg B ha^{-1} had adverse effects on growth and yield.

Negative responses of many field grown crops to high levels of B in irrigation water, were reduced when grown under salinity (achieved using mixture of salts) (Ferreyra et al. 1997). In other studies, using a mixture of chloride and sulphate salts, El-Motaium et al. (1994) reported salinity induced reduction in B uptake and accumulation in the stem of several Prunus rootstocks thereby decreasing B toxicity symptoms. As there was a negative relationship between B and SO_4^{2-} concentration in tissues, it was suggested that SO_4^{2-} could be responsible for the salinity–induced reduction of B in Prunus. However in neither study, the investigators were able to suggest the actual mechanism that supports this phenomenon such as direct ion interactions, reduced transpiration in salt-stressed conditions or both. The absorption of B is reduced from this substrate having high Ca particularly under calcareous conditions, which can induce B deficiency (Gupta et al. 1985). Therefore, it is difficult to distinguish the effect of SO_4 and Ca on uptake of B and its transport to shoot where a mixture of salts having both were used to achieve the desired salinity levels (Yadav et al. 1989; El-Motaium et al. 1994). Salinity also influenced the sub-cellular distribution of B cations and proteins in basal and apical sections of wheat. High B supply increased B concentration in all leaf parts, but was below 25 mg B kg^{-1} (on dry weight basis) in basal sections, whereas it exceeded 600 mg B kg^{-1} (on dry weight basis) in leaf tips. In basal leaf sections, intercellular soluble B concentration was double than intracellular concentrations of B (soluble) indicating some retention of excess B in the apoplast. Combined salinity and B toxicity stresses significantly increased soluble B concentrations in inter and intracellular compartments of basal leaf sections in comparison with either of the stresses occurring alone (Wimmer et al. 2003).

Molybdenum and Copper

Sodic soils contain high amounts of available Mo since its solubility increases with soil pH. Forage crops grown on these soils were found to contain high Mo concentrations that could cause toxicity to the animals, referred to as "Molybdenosis". Application of gypsum decreased Mo in plants due to the antagonistic interaction of SO_4 released from the applied gypsum with Mo absorption. However, application of gypsum also reduces the pH of the soil thus affecting solubility of Mo. Not much information is available on effect of salt stress on Mo and Cu concentration in plants. Salinity resulted in increased Mo concentrations in maize when the crop was grown in soil (Rahman et al. 1993), but there was no effect of salinity on Mo uptake from solution culture (Izzo et al. 1991). Likewise, the effect of salinity on Cu accumulation was also variable depending on the crop. Its concentration decreased in the leaf and shoot of maize grown either in salt-stressed soil (Rahman et al. 1993) or in saline solution cultures (Izzo et al. 1991) but in tomato, leaf Cu substantially increased in NaCl saline nutrient solution.

Conclusions

Plants/crops growing in salt affected soils are exposed to a number of unfavorable conditions like moisture stress, element toxicity, poor soil physical conditions, nutrients imbalance and their deficiency. Plants responses to these adverse conditions are complex and their requirement of different nutrients may not be same under salt stress conditions compared to that of non-stress. The relationships between salt stress and mineral nutrition of plants are equally complex as activity of nutrient elements is altered because of excess of potentially toxic ions (Na^+, Cl^-, SO_4^{2-}, CO_3^{2-}, and HCO_3^-) present in salt affected soils. These ions cause toxicity in plants after their uptake, and also have antagonistic effects on uptake of other nutrient elements like K, N, and P. pH induced changes in the solubility and availability of nutrients is another important factor. Salt affected soils have inadequate levels of some of the nutrients like N, whereas, availability of others such as Zn may be very low. A good number of published results both under controlled as well as field conditions, have shown that improving the soil nutritional status helped plants to grow and yield better under salt stress. However, in some of the reports increased application of nutrients (N, P, and K) did not produce the desired results, which is likely to be because of differences in growing conditions, level of salt stress, crops and their varieties used in the study. The present paper has focused on one of the major reasons for the aggravation of the adverse effects of salt stress on plant growth and yield because of inadequate supply of mineral nutrients, namely, nitrogen, phosphorus, potassium, calcium

and zinc. To get the maximum advantage from the applied mineral nutrients, they must be given in the right quantity, at the appropriate time and place, from a proper source and in the right combination. Nutrient application should synchronize with the growth stage of the plants when the requirement of nutrient is maximum. This is true for any situation, but more important under stress environment as adequate level of nutrients may alleviate, to some extent, the adverse effects of salinity and sodicity. Crops especially the horticultural crops, which are highly sensitive to Cl^- toxicity are likely to be benefited by adding more N as NO_3 to offset the adverse effects of Cl^- on its uptake. Similarly, Na induced Ca deficiency or K in plants could be corrected by adding Ca and K as nutrients

The above review has resulted in the identification of several gaps in addition to the need for systematic studies dealing with physiological aspects and interactions when multiple nutrient deficiencies occur under field conditions. Some of the issues need to be focused on are: (a) generating resource inventories on waterlogged and salt affected soils, and poor quality waters for appropriate land use planning, (b) improving the nutrient use efficiency, which is low in salt affected soils, (c) minimising the dependence on inorganic fertilizers, as the raw materials for their production are not infinite, (d) sustaining the productivity in post-reclamation phase in relation to soils and water quality vis-à-vis organic matter dynamics and carbon sequestration, and (e) breeding / developing / identifying varieties having higher nutrient use efficiency as well as tolerance to salt with the long term objective of multiple stress tolerance.

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Role of potassium in water stress management in dry land agriculture

Ch Srinivasarao • KPR Vittal • B Venkateswarlu

Abstract Potassium (K) deficiency is one of the important soil fertility constraints in increasing world food production. Rainfed agriculture, which extends over 85 m ha in India covering wide variety of soils and crops often, suffers from intermittent drought and water stress. Potassium has special role in rainfed agriculture as it enhances resistance to adverse environmental conditions such as drought. Potassium status of Indian soils varies from low to high depending upon soil type and management practices; however its application in rainfed crops is meager. Thus, for most of the rainfed crops, soil K reserves are major sources of crop K nutrition. Optimum K nutrition is known to improve water relations in crop plants through stomatal closure/opening mechanism. Present paper reviews the K status of Indian soils in rainfed regions, K removals by different crops, mechanism of K in water stress tolerance of crop plants and impact of K addition in water stress management and crop yields.

Keywords Potassium nutrition • K deficiency • water stress

Introduction

Crop production in the world has made a remarkable step forward since the sixties enabling to feed its steadily increasing population although the area of arable land remained almost the same. An analysis of the nutrient balances (Syers et al. 2001) for the period 1960-1998 for six Asian countries, indicated an overall annual K deficit of about 11 m t of K, which is 250 per cent more than the current K fertilizer use. Recent estimate of nutrient balances in world soils indicated the largest negative K balance in Asia followed by Africa and positive K balances in America and Europe (FAO 2003). In India, a considerable progress was made over the years in increasing the food grain production reaching a record level of 231 mt in 2007-08, yet it will require about 7-9 mt additional food grains each year if the

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rising population trend continues.

Two-thirds of the cultivated area in India is under rainfed farming. Rainfed agriculture support 40 percent of India's human population and two-thirds of the livestock. Ninety percent of the coarse cereals, 90 percent grain legumes, 80 percent oilseeds and 65 percent of cotton are grown in rainfed regions. However, rainfed areas suffer from a number of crop production constraints. Among them, low soil organic carbon, poor soil fertility, frequent droughts are important factors, which determine the productivity levels of dryland soils. As the food production increased with time, the number of deficient elements in Indian soils and crops also increased. Among the essential plant nutrients, potassium assumes greater significance since it is required in relatively larger quantities by plants. Besides increasing the yield, it improves the quality of the crop produce and improves N and P use efficiency. Among soil fertility problems, potassium deficiency is one of the emerging nutritional constraints for increasing productivity levels of dryland crops (Srinivasa-Rao and Vittal 2007; Srinivasa-Rao and Venkateswarlu 2009). Potassium nutrition has special significance in dryland crops as it is associated with crop tolerance to water stress condition, which is a common feature of dryland agriculture.

K status in rainfed agriculture

Information on K status in different agro-ecological regions of India is summarized in Table 1. Different soil types exist in these agro-ecological regions such as alluvial, medium and deep black soils, red and literitic soils. Potassium status of these soils varies depending on soil type, parent material, texture and management practices. In general, black soils with smectite as a dominant clay mineral, higher clay and CEC showed high levels of exchangeable K and medium to high non-exchangeable K content (Fig 1). Alluvial soils with higher contents of K rich mica with light texture showed medium level of exchangeable K and high of nonexchangeable K content. Red and lateritic soils with kaolinite as a dominant clay mineral and light texture showed low levels of exchangeable as well as nonexchangeable K content.

Apparently, rainfed crops in India, under compulsion to meet their K needs are mining soil K reserves. Under these circumstances, the amount of reserve K in specific soil and its release would be the most important factors for K nutrition of the crops (Srinivasarao et al. 1999). Besides, in rainfed crops optimum K nutrition plays a vital role in inducing resistance to withstand moisture stress and improve water-use efficiency during drought conditions (Mengel and Kirkby 1987). As most of the rainfed crops are deep rooted, contribution of sub soil K towards K nutrition is substantial.

Release studies indicated that despite the larger reserves of K in alluvial soils of U.P., Bihar and Rajasthan, the rate of K release is much slower as compared to

Table 1 Potassium status in different agroecological regions of India (Source: Subba-Rao and Srinivasa-Rao 1996).

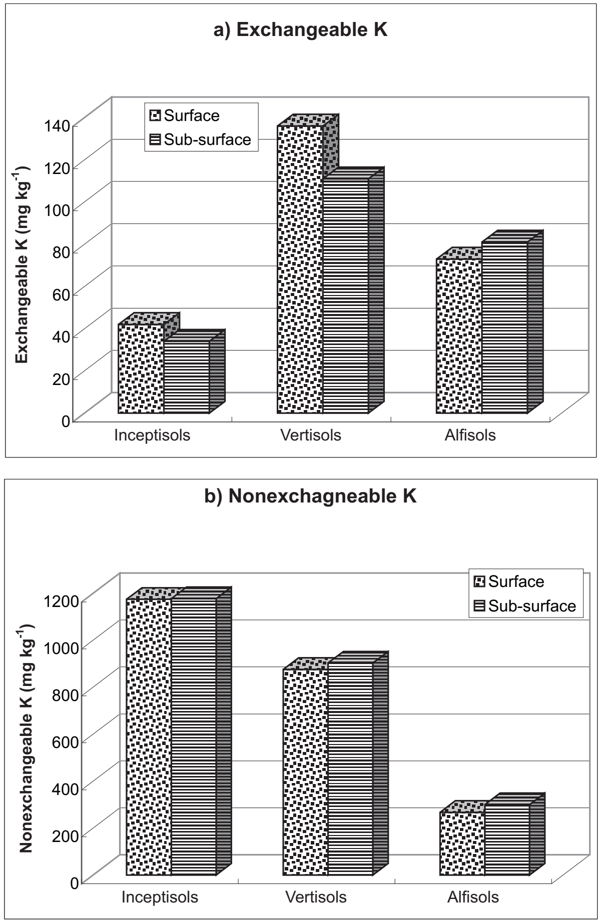
Agroec-logical region	States covered	Climate/Soil	Exchangeable K	Non exchangeable K
Region 2	Gujarat, Rajasthan, Harayana	Hot arid-black and alluvial	L-H	L-H
Region 3	A. P	Hot semi arid- red soils	L-M	L-H
Region 4	U.P., Rajasthan, Gujarat, M.P.	Hot semi-arid a Alluvial	M-H	H
Region 5	Rajasthan, Gujarat, M.P.	Hot semi-arid medium-deep black	H	M-H
Region 6	Maharastra, Karnataka, A.P.	Hot semi-arid Medium-deep black	H	M-H
Region 7	A.P.	Hot semi-arid Red and black	L-H	L-M
Region 8	Tamil Nadu, Karnataka, A.P.	Hot semi-arid Red loamy	M	L
Region 9	U.P.,Uttaranchal, Bihar,	Hot sub-humid alluvial	M	M-H
Region 10	M.P.	Hot sub-humid black	H	M-H
Region 11	M.P. Maharashtra	Hot sub-humid Red & yellow	H	M-H
Region 12	Jarkhand, M.P. Chattisgadh	Hot sub-humid Red & Lataritic, black	L-M	L
Region 13	Orissa, Jarkhand, Chattisgadh	Hot sub-humid Alluvial	M-H L-H	
Region 14	H.P, J&K, Punjab	Humid -Acidic alluvium	L-M	L-M
Region 15	West Bengal, Sikkim, Assam, Arunachal Pradesh	Hot-Sub humid-Terai acid soils	L-H	L-H
Region 17	Meghalaya	Per humid-red and lateritic	L-H	M-H
Region 18	A.P., T.Nadu, Orissa	Hot semi arid -coastal light	L-M	L-H
Region 19	Kerala	Per humid -lateritic	L-H	Low
Region 20	Andaman-Nicobar	Per humid-red loamy	M	M

L: low; M: Medium; H: High
Exchangeable K: Low: <50 mg kg^{-1}; Medium: 50-120 mg kg^{-1}; High: >120 mg kg^{-1}
Non-exchangeable K: Low: <300 mg kg^{-1}; Medium: 300-600 mg kg^{-1}; High >600 mg kg^{-1}

black soils. Hence under intensive cropping with high-yielding short duration genotypes, the soil K supply may not match with K demand by crop. Therefore, application of K to crops particularly in light textured acidic alluvial soils is essential to sustain higher productivity. Similarly, K application is essential on red and lateritic soils, as these soils possess low levels of soil K status as well as its buffering capacity (Sriniviasa-Rao et al. 1998).

In rainfed agro ecosystems, the soils are characterized by low to high available K status. Surface soils of Agra, S.K.Nagar, Bangalore, Hoshiarpur and Rakh Dhiansar were low in K, Faizabad, Phulbani, Ranchi, Anantapur, Akola, Hisar and Arjia were medium and at Rajkot, Indore, Rewa, Kovilpatti, Bellary, Bijapur and Solapur were high. Potassium deficiency is noticed in coarse textured alluvial soils, red and lateritic and shallow soils and soils which supported

Fig. 1 Exchangeable and nonexchangeable K status in different soil types in rainfed regions of India



continuous high yields without K addition (Srinivasarao et al. 2007; Srinivasarao and Vittal 2007). Vertisols and Vertic intergrades showed relatively high available K as compared to Inceptisols and Alfisols because of higher clay content and smectitic clay. Profile mean of available K varied from 138.8 to 195.1 kg ha^{-1} under rice based production system, from 129.2 to 188.8 kg ha^{-1} under groundnut system, 322.3 to 407.5 kg ha^{-1} under soybean system, from 76.7 to 272.3 kg ha^{-1} under cotton system, from 365.4 to 500.4 kg ha^{-1} under rabi sorghm system, from 85.1 to 163.1 kg ha^{-1} under pearlmillet system, 53.0 kg ha^{-1} under fingermillet and from 55.6 to 109.4 kg ha^{-1} under maize based production system.

K requirements of different dry land crops

Intensive cropping invariably results in heavy withdrawal of nutrients from soils and its sustenance largely depends upon the judicious application of inputs commensurate with nutrient uptake. Nutrient uptake values generally provide a reliable estimate of nutrient requirements under varying agro-ecological regions which would form the basis for the development of a sound fertilizer recommendation strategy for realizing higher productivity and maintaining soil fertility. The average uptake of major nutrients by crops at 100 percent NPK treatments of selected intensive cropping systems indicated that in most of the cropping systems, K uptake exceeded N, especially when three crops are taken in a year like maize-wheat-cowpea (f), rice-wheat-jute fibre and sorghum-sunflower hybrids. Potassium uptake in relation to N and P_2O_5 is presented in some important dryland crops in India (Table 2)

Table 2 Nutrient uptake of some important rainfed crops in India (Source: Srinivasarao and Venkateswarlu, 2009)

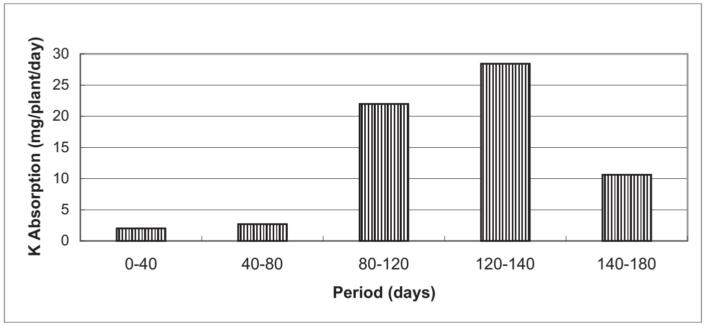
Crop	Produce	kg nutrient tonne^{-1} produce		
		N	P_2O_5	K_2O
Sorghum	Grain	22.4	13.3	34.0
Pearl millet	Grain	42.3	22.6	90.8
Rice	Grain	20.1	11.2	30.0
Chickpea	Grain	46.3	8.4	49.6
Groundnut	Grain	58.1	19.6	30.1
Soybean	Grain	66.8	17.7	44.4
Sunflower	Grain	56.8	25.9	105.0
Cotton	Seed	44.5	28.3	74.7

However, in case of potassium, K release rates should be matched with daily K uptake by different crops (Srinivasarao et al. 1999; 2006). Some of the K loving crops like cereals, tuber crops, banana, sugarcane, tobacco, tea have higher uptake rates. For example, rate of K absorption by pigeonpea over a period of time (Fig. 2) shows maximum K absorption during 80 to 140 days (Narasimhachary 1980). When soils are low to medium such as light textured alluvial, red and lateritic, crop needs K fertilization specially to meet the K absorption rates during these critical stages of crop plants.

K nutrition and water stress

The major limiting factor for crop yield in arid and semi-arid regions is the amount

Fig. 2 Rate of K absorption in pigeonpea under rainfed conditions



Source: Narasimhachary 1980

of soil moisture available to plants during the growing season. Soil moisture influences K^+ uptake by plants by affecting root growth and the rate of K^+ diffusion in the soil towards the root (Surya-Kant and Kafkafi 2002). Mackay and Barber (1985) tried to resolve the effects of actual root growth as compared with the K^+ diffusion rate as affected by moisture. At the lower side of the optimal soil moisture content, increasing soil moisture increased the effective diffusion coefficient of K^+ and therefore increased K^+ uptake. Increasing the moisture content above the optimum resulted in slow root growth due to oxygen shortage. The reduction in root elongation was reflected in lower K^+ uptake. The rate of root elongation is a crucial parameter in the uptake of nutrients that are strongly adsorbed to the soil and their concentration in the soil solution is usually very low (Kafkafi 1991). Combined effects of low temperatures and low moisture can be alleviated by increasing the concentration of K^+ in the soil (Kafkafi 1990).

Potassium has substantial effect on enzyme activation, protein synthesis, photosynthesis, stomatal movement and water relations (turgor regulation and osmotic adjustment) in plants (Marschner 1995). Increased application of K^+ has been shown to enhance photosynthetic rate, plant growth, yield, and drought resistance in different crops under water stress conditions (Egilla et al. 2001; Pervez et al. 2004; Thalooth et al. 2006; Yadav et al. 1999). K-fed plants maintained higher leaf water potential, turgor potential and relative water content and lower osmatic potential as compared to untreated plants of Vigna radiata (Nandwal etl al.1998), maize (Premachandra et al. 1991), and wheat (Pier and Berkowitz 1987; Sengupta et al. 1989) grown under water stress. Nodulation, nitrogenase activity and dry matter yield increased with incremental K^+ supply in broad bean grown at moisture level of only ¼ of field capacity (Adb-Alla and Wahab 1995). K^+ is predominant in accumulating solute during drought in tropical grasses (Ford and Wilson 1981), soybean (Itoh and Kumura 1987), maize (Premachandra et al. 1991), cotton (Pervez et al. 2004) and olive trees and sunflower (Benlloch-

Gonzaliz et al. 2008) and significantly contributed to osmotic adjustment.

The function of stomata is to control water loss from the plant via transpiration. When K^+ is deficient, the stomata cannot function properly and water losses from plant may reach damaging levels (Gething 1990). This has been demonstrated in field experiment in barley in which plants were exposed to hot wind which caused an immediate increase in transpiration rate. The severely K^+ deficient plants took long time to react by closing stomata and lost internal moisture, while the well K^+ supplied plants responded quickly in closing stomata and preserved internal moisture. The stomata close in response to water stress, thereby reduction in carboxylation efficiency of the chloroplasts. Stomatal closure for long time leads to photoreduction of O_2 to toxic O_2 species. This effect of drought can be more severe when plants are grown with inadequate supply of K^+, as K^+ itself is required for stomatal movement (Humble and Raschke 1971). The larger K^+ requirement of water stressed plants can be related to the protective role of K^+ against stress induced photo-oxidative damage and has been well documented (Pier and Berkowitz 1987; Sengupta et al. 1989). Under water stress, the photosynthetic efficiency of plants is reduced drastically (Table 3) as a consequence of chloroplast dehydration (Berkowitz and Kroll 1988). The chloroplasts lose large amounts of K^+ with a simultaneous decrease in photosynthesis. Hence, application of more K^+ than that usually applied for irrigated plants was necessary to maintain photosynthetic activity (Sengupta et al. 1989). In wheat experiments, Pier and Berkowitz (1987) observed 66-113 percent higher photosynthetic rates in plants fertilized with above normal K^+ than those under standard fertilization, indicating that leaves of plants grown in very high internal K^+ levels have partially reversed the dehydration effects on photosynthesis (Pervez et al. 2004).

The plant's K^+ status also affects the ease with which it can extract water from soil. Plants adequately supplied with K^+ can utilize the soil moisture more efficiently than K^+ deficient plants (El-Hadi et al. 1997). Cell elongation, the basic event of plant growth, is initiated by wall relaxation, causing osmotic potential-

Table 3 Effect of water stress and K^+ supply on net photosynthesis rate in wheat leaves (Source : Sengupta et al. 1989)

K^+ (mM)	Photosynthesis (µmol CO_2 m^{-2} S^{-1})		
	Water stress in leaves		
	Low	Mild	Severe
0.2	38	11	2
2.0	47	42	21
6.0	46	45	28

driven water uptake and turgor-driven cell expansion, consequently enhanced by K^+ application (Lindhauer 1989). Improved cell expansion and growth, set up a pressure gradient between the root and its surrounding which causes water to be taken up (Gething 1990). Lindhauer (1985) showed that K^+ fertilization besides increasing dry matter production and leaf area development greatly improved the retention of water in the plant tissues even under conditions of sever water stress. The K^+ is found in the plant cell in two distinct compartments (Leigh 2001), the cytosol and the vacuole. It is now clear that K^+ transport through plant cell membranes is done through specific protein channels (Maathuis et al. 1997). Any shortage of water cause plants to lose turgor, K^+ deficient roots have lower sap osmotic pressure and turgor. Stretch activated K^+ channels could provide turgor-responsive transport pathway for K^+ (Leigh 2001). On the other hand, water stress had a stimulating effect on proline accumulation which is a mechanism for plants adaptation to water stress and proline content significantly improved with K supply (Thalooth et al. 2006).

K nutrition and water stress management

Crops suffer from K deficiency on red and lateritic soils, light textured and acidic alluvial soils and acid sulphate soils. Incidentally most of these soils are under rainfed regions and crops are exposed to mild to severe droughts depending upon amount and distribution of rainfall. Potassium being associated with the crop tolerance to water stress condition, optimum K nutrition is one of the water stress management strategies in rainfed crops.

The finger millet crop was irrigated in four schedules viz., Control 85-90 percent; S_1 65-70 percent; S_2 25-30 percent of field capacity and three levels of applied K (0, 30, 60 and 90 mg kg^{-1}) under pot conditions. Water stress reduced the relative water content, osmotic potential, nitrate reductase activity and grain yield but proline and stomatal resistance have increased. Application of 30 mg kg^{-1} K under control and S_1 and 60 ppm under S_2 and S_3 levels mitigated the adverse effects of water stress and increased the grain yield (Yadav et al. 1999). Watered K sufficient tomato plants had significantly higher photosynthetic rates than the watered K deficient plants. Water potential of the K sufficient plants decreased by 1.01 and that of the K deficient plants only by 0.19 MPa three days after the last watering. The photosynthesis (Table 4) was more sensitive to reductions in plant water potential in K deficient plants compared to the K sufficient plants (Behboudian and Anderson 1990).

The amount of soil moisture available to plants in arid and semi-arid regions is a major limiting factor for crop yield. Under such conditions, potassium fertilization proved helpful in mitigating the adverse effects of water stress. The interaction of plant K status and water stress in mustard, sorghum and groundnut

Table 4 Effects of potassium deficiency and water stress on the rate of photosynthesis in tomato leaves. (Source: Behboudian and Anderson 1990).

Treatment		Leaf water	Photosynthesis
Potassium	Irrigation	potential (MPa)	(μ mol m^{-1} s^{-1})
+K	Watered	-0.46	6.47
+K	Stressed	-1.47	2.50
-K	Watered	-0.40	3.97
-K	Stressed	-0.59	2.44
LSD ($P < 0.01$)		0.31	2.33
LSD ($P < 0.05$)		0.22	1.66

Values are means of 4 replicates. On each replicate photosynthesis was measured on 3 leaves and averaged

(Umar 2006) showed that water content of the leaf tissue was significantly increased by K application and the highest increase in RWC was 14.7 percent, 17.4 percent and 22.8 percent under normal conditions, and by 8.7 percent, 19.9 percent and 17.7 percent under water stress conditions in mustard, sorghum and groundnut, respectively. Water stress caused grain yield reductions and K application could enhance yield to a great extent. Production of above ground biomass, grain yield and RWC were highly correlated with the tissue K concentration, showing that concentration of K^+ in leaves played a vital role in increasing water stress resistance and stabilizing yield in the crops studied. Cakmak (2005) reported several examples emphasizing the role of K in alleviating the adverse effects of drought on crop production.

As competition for the limited water supply available for irrigation of horticultural crops increases, research into crop management practices that enhance drought resistance, plant water-use efficiency under limited water supply become essential. The effect of K nutrition status on the drought resistance of *Hibiscus rosa-sinensis* L. cv. Leprechaun (*Hibiscus*) was studied with Hoagland's nutrient solution, modified to supply K as K_2S0_4, at 0 mM K (Ko), 2.5 mM K (K2.5), and 10 mM K (K10), under two irrigation regimes (drought stressed [DS] and non-drought stressed [non-DS]). Regular irrigation and fertigation were adopted for 54 days, and drought stress treatment (initiated on day 55) lasted for 21 days; while non-DS control plants continued to receive regular irrigation and fertigation (Table 5). Following the 21-day drought stress period plants were labeled with 86Rb to determine the percentage of post-drought stress live roots. Both K deficiency (Ko) and drought stress reduced shoot growth, but drought stress increased root growth and thus the root/shoot ratio. At Ko, plants were K-deficient and had the lowest leaf K, Fe, Mn, Zn, Cu, B, Mo and highest Ca concentrations. Although the percentage of live roots was decreased by drought stress, K2.5 and K10 plants (with similar percent live roots) had greater root survival ratio after drought treatment than the K-deficient plants. These observations indicate that adequate K nutrition can improve drought resistance and root longevity in Hibiscus rosa-sinensis (Egilla et al. 2001).

Table 5 Effects of K and drought stress on midday leaf water relations of Hibiscus rosa-sinensis L. cv. Leprechaun during a 21-d drought stress period. Means of 2 leaves from 3 plants per K treatment ± S.E., n = 6, Ψ_I = leaf water potential, Ψ = leaf osmotic potential, Ψ_P = leaf pressure potential [MPa], P_N = net photosynthetic rate [µmol m^{-2} S^{-1}], E = transpiration rate [mmol m^{-2} S^{-1}], g_s = stomatal conductance [mol m^{-2} S^{-1}]. D_1 = day 0, D_3 = day 21; K_0=0.0 m M K, $K_{2.5}$=2.5 m M K, K_{10}= 10 m M K (Source: Egilla et al. 2005).

Time [d]	K supply	Ψ_I	Ψ	Ψ_P	Ψ_P/Ψ_I
0	K_0	-0.62±0.08	-1.99±0.04	1.37±0.09	2.50±0.44
	$K_{2.5}$	-0.43±0.04	-1.87±0.09	1.44±0.10	3.65±0.63
	K_{10}	-0.48±0.05	-2.18±0.22	I. 70±0.22	3.90±0.74
21	K_0	-1.50±0.04	-2.10±0.14	0.59±0.13	0.40±0.08
	$K_{2.5}$	-1.52±0.02	-2.23±0.08	0.71±0.09	0.47±0.06
	K_{10}	-1.61±0.04	-2.37±0.11	0.76±0.13	0.48±0.09
Time [d)	K supply	P_N	E	g_s	P_N/E
0	K_0	17.95±063	8.32±0.38	0.86±0.07	2.17±0.07
	$K_{2.5}$	22.69±0.47	9.23±0.35	1.17±0.07	2.47±0.05
	K_{10}	21.21±0.88	9.15±0.39	0.99±0.05	2.34±0.05
21	K_0	5.39±0.64	2.98±0.41	0.17±0.03	1. 92±0.22
	$K_{2.5}$	8.27±1.28	3.13±0.39	0.18±0.01	2.64±0.23
	K_{10}	6.04±0.99	1.98±0.23.,	0.16±0.03	2.95±0.17

In an another set of experiments, Egilla et al. (2005) reported that compared to K deficient plants, adequate K supply improved the leaf water content and leaf water relations and generally sustained rates of net photosynthesis, transpiration and stomatal conductance in drought stress and non drought stress plants.Considerable osmotic adjustment occurred in pearlmillet plants experiencing water deficit under high K supply (Ashraf et al. 2001). Chlorophyll a and b contents increased significantly with increase in K supply under well watered conditions, but under water deficit they increased only in ICMV 94133. Leaf water potential and osmotic potential of both lines decreased significantly with the imposition of drought and leaf water potential was increased with increase in K supply under water stress conditions.

Two major crops with greatly differing botanical characteristics, olive tree and sunflower, were studied whether moderate K^+ starvation inhibits water-stress induced stomatal closure and if it is a generalized phenomenon (Benlloch-Gonzalez et al. 2008). The olive is a slow-growing, woody plant displaying considerable water-use efficiency in drought situations. The sunflower is a fast-growing, herbaceous plant, whose water and nutrient uptake mechanisms are highly efficient. The new data obtained here on olive trees and sunflowers showed that moderate potassium starvation inhibits water-stress-induced stomatal closure, which suggests that it can be universal in nature. Results for olive trees also suggest some level of intra specific genetic variability with regard to the effect of potassium deficiency on shoot growth and stomatal conductance.

Vigna radiata L. plants were grown in greenhouse at moisture content of sand (SMC) of 12.0±0.5 percent. At flower bud initiation stage i.e. 45-50 days after sowing, the SMC was decreased to 3.5±0.5 percent, and the effects of applied potassium (0, 2.56 and 3.84 mmol dm3) were studied (Nandwal et al. 1998). During water stress, K fed plants maintained higher leaf water potential and relative water content (RWC) of leaves and nodules and lower osmotic potential as compared to untreated plants. The proline content was higher in nodules than in leaves sowing their difference in degree of stress (Table 6). K fed plant showed higher C and N content in stem, roots and nodules than untreated plants. Dry masses of different plant parts were also increased in K-fed plants.

Cotton, a major world fibre crop experiences drought during its growth, which significantly reduce its growth and yield. The effect of potassium nutrition (0, 6.25, 12.50, 25.00 g $(K)m^{-2}$) of K_2SO_4 or KCl) on gas exchange characteristics and water relations in four cultivars (CIM-448, CIM-1100, Karishma, S-12) of cotton were assessed under an arid environment (Pervez et al. 2004). Net photosynthetic rate (PN) and trasnpirtation rate (E) increased with increased K supply. The leaf pressure potential increased significantly by the addition of 25.00

Table 6 Effect of potassium on proline content [µg g^{-1} (d.m.)] of leaves and nodules in Vigna radiata under drought and rehydration (Source: Nandwal et al. 1998).

	Leaves control	Stress	Recovery	Nodules control	Stress	Recovery	
K0	129	1989	400	488	6204	1132	
K1	123	2696	546	455	6013	1022	
K2	150	2436	565	432	5368	1041	
C.D. at 5 % level							
	K	S	K x S		K	S	K x S
Leaves	160	160	278	Nodules	295	295	487

g(K) m^{-2} compared to zero K level. The water use efficiency was improved by 24.6 percent under the highest K dose compared to zero K. There were positive correlations between K doses and Pn, E, Ψ_s and Pn/E.

High potassium supply had a positive effect on nitrogen fixation, on shoot and root growth and on water potential in both water regimes. With common bean, in both water treatments (sufficient and water stress), K could increase the water potential substantially. The values were -0.83, -0.56 and -0.27 MPa for 0.1, 0.8 and 3.0 mM K in the low water treatment and -0.31, -0.15 and -0.07 MPa for the high water treatment, respectively. These data are consistent indicating that high K fertilization can at least in part compensate water shortage and K concentration is an essential factor determining plant resistance to water stress. This would support the view that K helps maintain the osmatic potential of plant cells, an increasingly critical problem with increasing water stress. The beneficial effect of high K supply on growth was generally similar in both water treatments with the exception that in faba bean the beneficial effect of 0.8 mM K compared to 0.1 mM was more pronounced in the low water treatment than in the high water treatment. The beneficial effect of high K under water stress can certainly in part, be explained by the fact that under conditions of restricted water flow into the roots, an increase in nutrient concentration will lead to an increased nutrient intake per unit of water uptake (Sangakkara et al. 1996).

Conclusions

The excess K^+ in the leaf partially protects photosynthesis from the deleterious effects of water stress. The protective effect appears to be mediated by extrachol-oroplantic K^+ in the plant cells, possibly acting on chloroplast photosynthesis through the mechanism of a K^+/H^+ ant port system. Stomatal closure in water stress conditions is related with K^+ transport and also associated with high proline content of the plant parts. Thus potassium is needed at high concentrations inside the plants from early stages of vegetative growth phase. However, external K application to different crops should be recommended depending upon soil status of exchangeable and reserve K and crop K requirements.

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Characterization of iron toxic soils of Orissa and ameliorating effects of potassium on iron toxicity

GN Mitra • SK Sahu • RK Nayak

Abstract Iron toxic soils of Orissa are located in red and laterite soil region especially in low lands adjacent to uplands, which enrich these soils with lateral flow of soluble iron during rainy season. The dominant iron bearing minerals in these soils are chlorite, garnet, magnetite and siderite. The soils were classified as Aquic Haplustepts, Fluventic Haplustepts, Kanhaplic Rhodustalfs and Kandic Paleustalfs. DTPA-Fe ranged from 105-570 mg kg^{-1} and pH 4.5-6.8. DTPA-Fe showed significant correlations with pH, K, Ca, Mg and Mn and all these factors collectively contributed 85% towards iron toxicity. Significant negative correlations were found between Leaf-Fe and soil characteristics such as, clay, pH, K, Ca, Mg, Zn and Mn. Out of 19 long duration (135 days and more) and 20 medium duration (100 - 125 days) rice varieties, eleven each from long and medium duration varieties were found to be tolerant to Fe-toxicity. All the tolerant rice varieties gave yields of 19.1 - 36.3 q ha^{-1} against the yields of 5.2 - 26.5q ha^{-1} in susceptible varieties. The toxic effects of Fe could be alleviated by application of K at 30-90 mg kg^{-1}. On an iron toxic soil (DTPA-Fe, 396 mg kg^{-1}) application of K at higher doses could alleviate effects of iron toxicity. Leaf bronzing disappeared and some of the yield parameters such as thousand grain weight, percent filled grains etc. improved at higher doses of K application. The grain yield of Fe-susceptible rice variety; Jaya doubled and of tolerant rice variety; Mahsuri increased by one and half times due to application of 120-160 kg K_2O ha^{-1}. Since soils of Orissa in general are iron rich and fertilizer consumption is very low (57 kg ha^{-1}, 2007), there is considerable nutrient imbalance in the soil. This is conducive to cause iron toxicity in soil even at sub-toxic levels of Fe. It is suggested that the recommended dose of K for rice be increased form the current 30 kg ha^{-1} to 60 kg ha^{-1}.

Keywords Iron toxicity • potassium • soils of Orissa

Introduction

Iron toxicity in India is generally associated with iron rich red and lateritic soils.

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These soils occur in the southern, eastern and northeastern regions to a large extent and in the central and western region to a limited extent. They constitute 28 per cent of the soils of the Country (Sehgal 1993). These soils are excessively to well drained, acidic, with low CEC and organic matter content, and have mixed or kaolinitic clay mineralogy enriched with sesquioxides. They suffer from toxicity of Al, Fe, and Mn, and deficiencies of N, P, K, Ca, and Mg, and also some other micronutrients. These soil groups come under the taxonomic orders Alfisols, Ultisols and Oxisols occurring in association with Entisols and Inceptisols. They have moderate to high productive potential for export-oriented crops, such as tea, coffee, cocoa, cardamom, cloves etc. However all other major crops such as, cereals, pulses, oilseeds, fruits and vegetables are grown in these soils with moderate to low yields.

Iron rich soils of Orissa and the problem of iron toxicity

Soils of Orissa are generally rich in iron with DTPA-Fe ranging from 8.2-356.0 mg kg^{-1} (Sahu and Mitra 1992; Mitra et al. 2002). Red and lateritic soils contain 17.8-356.0 mg kg^{-1} of DTPA-Fe (Mitra et al. 2006). The Fe content of these soils increases at lower depths (Mitra et al. 2006, Nayak, 2008, Sahu et al. 1990). During monsoon rains in the wet season (June to September) soluble Fe^{++} iron from anaerobic lower depths migrates to the surface and increases its iron content to sub-toxic/ toxic levels. In a rolling topography and with heavy monsoon downpour (1482 mm) there is considerable lateral flow of Fe-containing water from the adjacent uplands to mid- and lowlands. This increases their Fe content to toxic levels. Rice grown under such lowland water logged condition suffers from iron toxicity. Poorly drained sandy soils in valleys receiving interflow water from adjacent upland soils with lateritic horizon (Plinthudults) showed iron toxicity in Sri Lanka, Kerala and Orissa in India and Sierra Leone (van Breemenn and Moormann 1978).

The alluvial soils of Orissa including deltaic alluvium contain 15.8-153.2 mg kg^{-1} DTPA-Fe. The coastal saline soils contain 1.1.6-107.8 mg kg^{-1} DTPA-Fe. The symptoms of leaf bronzing in rice grown in the lateritic soils of Research Farm of Orissa University of Agriculture & Technology were suggested to be due to Fe toxicity (Sahu 1968). The problem again appeared in 1972, when a long term fertiliser experiment with rice-rice cropping sequence was laid out in a low land about 100m from an upland lateritic soil. The control plot showed symptoms of iron toxicity, which disappeared in treatments receiving higher doses of potassium. A deep ditch was dug up to prevent inflow of Fe from the uplands and drainage helped to control Fe-toxicity in the this experiment. The land adjacent to the upland with high Fe content was used to further study the problem of Fe-toxicity.

The total area under iron toxic soils in Orissa is estimated to be 52,000 ha. The major crop, which suffers from iron toxicity, is low land rice. Iron toxicity symptoms as observed are in conformity with the observations of Tanaka and Yoshida (1970), van Breemann and Moormann (1978). These symptoms manifest in soil, leaf, root, grain and crop yield. Brick red oily scum floating on surface water around the corners of field bunds is a common feature of iron toxic soils (Benckiser et al.1982). Roots become bushy and turn brown to black due to heavy deposition of oxides of iron and there is near absence of white roots. The seed coats become tinged with brown spots.

Classification of iron toxic soil and status of nutrients

Four pedons of Fe toxic soils were used for classification. The iron bearing minerals present in the fine sand fraction of these soils (Table 1) showed that the chlorite was the dominant mineral followed by magnetite, garnet and siderite.

Table 1 Fe bearing minerals (%) in fine sand fraction of Fe-toxic soils

Sl. No.	Name of the dominant mineral in soils	Formula of ironoxide mineral in soils	Names of locations				Mean
			Bhuba-neswar	Chiplima	Gajmar	Duburi	
1.	Chlorite	Fe (SiO_4O_{10}) OH_8	3.0	2.0	4.0	4.0	3.2
2.	Garnet	Fe_3 Fe_2 $(SiO_4)_3$	1.0	0.5	1.5	1.0	1.0
3.	Magnetite	Fe Fe_2 O_4	2.0	1.5	0.5	3.5	1.9
4.	Siderite	Fe (CO_3)	0.5	0.5	1.0	1.0	0.7
	Total		6.5	4.5	7.0	9.5	6.9

Source: Nayak 2008

The profile distribution of different forms of iron

In all the four pedons the quantity of iron was in the order of total-Fe > oxide-Fe > DTPA-Fe (Table 2). Total Fe and Fe-O increased with depth. Total Fe and Fe-O of Pedon-1 and 2 were less than Pedon-3 and 4 in corresponding horizons indicating that with similar source of iron in all the type of iron bearing minerals, quantities of Fe differed of the (Douli and Mustafi 1997; Khan et al. 1997; Patil and Dasog 1997). DTPA-Fe, which is considered the most appropriate form of available Fe, decreased with depth indicating the presence of less active forms of Fe (Suresh and Savitri 2001).

Taking into account all other parameters such as, morphology of pedons (site characteristic, slope, surface condition, parent material, groundwater table, natural vegetation, erosion, surface drainage, land use, genetic horizons, their depth and description, the iron toxic soils were classified according to “Keys to soil taxonomy' USDA (1998) as given in Table 3.

Table 2 Profile distribution of different forms of iron

No. and name of the pedon	Depth (cm)	Total Fe (%)	Free iron oxide (%)	DTPA-Fe (mg kg^{-1})
1. Bhubaneswar	0-17	3.8	0.52	428
	17-33	4.8	0.98	398
	35-53	6.3	1.23	384
	53-120	5.8	1.78	372
2. Chplima	0-12	4.0	0.69	272
	12-39	4.8	1.09	166
	39-69	6.2	1.21	151
	69-100	6.6	1,48	148
3. Gajamara	0-15	4.6	0.84	460
	15-33	5.0	1.23	380
	33-93	6.4	1.46	210
	93-157	7.2	1.90	190
4. Duburi	0-15	4.5	0.78	425
	15-41	5.2	1.12	318
	41-72	6.6	1.36	186
	72-110	6.9	1.85	110

Source: Nayak 2008

Table 3 Classification of iron toxic soils of Orissa

Pedon No.	Order	Sub-order	Great group	Sub-group	Family	Series
1.	Inceptisols	Ustepts	Haplustepts	Aquic Haplustepts	Coarse, loamy, mixed, hyperthermic	Bhubaneswar
2.	Inceptisols	Ustepts	Haplustepts	Fluventic Haplustepts	-do-	Chiplima
3.	Alfisols	Ustalfs	Rhodustalfs	Kanhaplic Rhodustalfs	-do-	Gajamara
4.	Alfisols	Ustalfs	Paleustalfs	Kandic Paleustalfs	-do-	Duburi

Source: Nayak, 2008

Physical properties and nutrient status

The iron toxic soils of Orissa were sandy loam to clayey in texture and had a pH range of 4.6-6.8. A total of 62.5% of the soils were strongly acidic (pH 4.5-5.5), 33% moderately acidic (5.6-6.5) and 4.5% slightly acidic (6.6-7.0). Organic C content of 75% of the samples was low (< 5.0 g kg^{-1}) and 25% medium (5.0-7.5 g kg^{-1}). The iron rich soils with relatively high organic matter show iron toxicity under submergence (Mohanty and Patnaik 1977; Tanaka and Yoshida, 1970). Available N content of 96.6% of the samples was low (less than 125 mg kg^{-1}), 25% were low in Available P (4.5 mg kg^{-1}) and 52.3% were low in Available K (59 mg kg^{-1}). The percentage of samples medium in N (125-250), P (4.5- 11.0) and K (59-140 mg kg^{-1}) were 3.4, 72.7 and 45.4, respectively. None of the sample was high in N (250 mg kg^{-1}), where as 2.3% of samples were high each in P (11 mg kg^{-1}) and K (140 mg kg^{-1}). The values of exchangeable Ca and Mg were low, 1.7-4.8 and 0.8-2.5 (c mol (p+) kg^{-1} respectively for all the samples due to low pH of the iron toxic soils. The lower limit of Fe content to show iron toxicity symptoms in rice has been reported as 40-100 mg kg^{-1} (Panabokke 1975), 30 mg kg^{-1} for soils with low nutrient content and 300-400 mg kg^{-1} with fertile soils. On the basis of 100 mg kg^{-1} astoxic limit all the soil samples (with 105 to 750 mg kg^{-1} DTPA Fe) were above the toxic limits. The limits of adequacy of DTPA-Zn, Mn and Cu have been fixed at 1.20, 4.0 and 0.40 mg kg^{-1} by the All India coordinated Project on Micronutrients and Pollutants. On the basis of these limits about 10% of the iron toxic soils of Orissa have adequate levels of Zn, 94% adequate Mn and 98% adequate Cu. Benckiser et al. (1982) and Tadano and Yoshida (1978) had reported such nutrient imbalance in iron toxic soils.

Interaction of DTPA-Fe with other soil nutrients

DTPA-Fe showed non-significant positive correlation with clay and Cu but negative and significant correlations with pH, K, Ca, Mg and Mn. Zn had a positive correlation with DTPA-Fe. Sahu et al. (1990) had reported a significant negative correlation between DTPA-Fe and clay while analyzing 48 soil samples representing all the soil groups of Orissa. The difference is probably due to selection of only iron toxic soils from specific locations. Multiple regression equation was developed considering DTPA-Fe as dependent variable and other soil properties as independent variables. The equation was as follows:

DTPA-Fe = 99.8 + 128.3 silt + 257.0 clay + 459.4 pH + 199.7 OC – 1.1 N + 15.9 P – 2.0 K – 119.8 Ca –69.5 Mg + 196.7 Zn – 1.2 Mn + 13.1 Cu; R^2 = 0.850

All the factors mentioned above collectively contributed 85% towards iron toxicity. The major contributors for iron toxicity were pH (45.8%), Clay (14.3%), organic carbon (8.6%) and silt (3.5%). Soil acidity plays a significant role in solubilising Fe from iron rich lateritic soils of Orissa and causing iron toxicity to low land rice. Clay and organic carbon have relatively lower contribution, as the soils are predominantly sandy or sandy loam and organic carbon contents are low.

Fe contents in rice leaf

Iron contents of leaves affected by iron toxicity from 57 locations (Table 4) were in the range of 360-915 mg kg^{1}. Such variation is expected since a number of factors such as variety grown and its tolerance to iron toxicity, soil conditions prevailing at different locations, concentrations of other nutrients in soil and plants, and environmental factors (e.g., temperature, solar radiation) (van Breemann and Moormann 1978). Taking 300 mg kg^{1} as threshold limit (Tanaka and Yoshids 1970) all the samples of rice leaves had toxic concentrations of Fe (360-915 mg kg^{1}).

Table 4 Nutrient content of rice leaves affected by iron toxicity from different locations of Orissa

District	Fe (mg kg^{1})	P %	K %	Ca %	Mg %	Mn (mg kg^{1})	Zn (mgkg^{1})
Khurda (20)*	450-915	0.07-0.12	0.62-0.91	0.29-0.48	0.13-0.23	113-170	15-28
Puri (4)	418-490	0.11-0.12	0.88-0.94	0.44-0.49	0.20-0.23	165-176	27-28
Nayagarh (5)	420-560	0.09-0.12	0.81-0.95	0.43-0.48	0.20-0.23	158-177	25-29
Jajpur (5)	377-485	0.10-0.12	0.92-1.10	0.46-0.50	0.22-0.24	166-182	27-32
Dhenkanal (5)	400-415	0.09-0.10	0.98-1.01	0.48-0.49	0.3-0.24	176-181	29-30
Keonjhar (5)	375-400	0.10-0.11	1.00-1.12	0.49-0.50	0.22-0.23	179-182	30-32
Balasore (4)	360-400	0.10-0.11	1.14-1.21	0.48-0.51	0.22-0.24	182-186	29-31
Bargarh (5)	360-451	0.09-0.11	1.05-1.20	0.44-0.48	0.19-0.24	173-184	28-32
Sambalpur (4)	422-465	0.09-0.10	1.05-1.12	0.41-0.43	0.19-0.20	176-180	28-30
All (57)	360-915	0.07-0.12	0.60-1.21	0.29-0.51	0.13-0.24	113-186	15-32

* Values in parenthesis indicate number of samples

The leaf-Fe was significantly and negatively correlated with soil characteristics such as clay, pH, K , C, Mg, Zn, and Mn. Significant positive correlations were observed for Fe (table 5). Leaf-Fe had significant negative correlations with leaf-P, K, Ca, Mg, Zn and Mn. High content of Fe in leaf led to deficient contents of other nutrients.

Table 5 Correlations between leaf Fe and soil characteristics and leaf nutrients

Soil Parameters	(r)	Plant Parameters	(r)
Clay	-0.282*	-	-
PH (1:2)	-0.540**	-	-
OC (g kg^{-1})	0.153	-	-
P (mg kg^{-1})	0.232	P (%)	-0.809**
K (mg kg^{-1})	-0.734**	K (%)	-0.912**
Ca (cmol (p+) kg^{-1}	-0.518**	Ca (%)	-0.956**
Mg(cmol (p+) kg^{-1}	-0.389**	Mg (%)	-0.954**
Fe (mg kg^{-1})	0.709	Fe (mg kg^{-1})	1.0**
Zn (mg kg^{-1})	-0.194**	Zn (mg kg^{-1})	-0.988**
Mn (mg kg^{-1})	-0.389**	Mn (mg kg^{-1})	-0.995**
Cu (mg kg^{-1})	0.246	Zn (mg kg^{-1})	-

Tolerance of iron toxicity by rice varieties

A number of rice varieties of different duration currently grown in Orissa were tested for their tolerance to iron toxicity (IRRI 1980). Some of the tall traditional varieties such as, T-90, T-141, T-1242 were found to have greater tolerance to iron toxicity. Yield levels of tolerant varieties were also considerably higher than susceptible varieties. The mechanism involved could be their root oxidizing power. The presence of aerenchyma (tissue containing enlarged gas spaces) in the roots of rice is considered to contribute to its healthy growth under waterlogged conditions. Aerenchyma occupies 40-50% of the total cross sectional area of roots of waterlogged rice whereas under upland conditions it occupies 25-30% (Kimura 1993). These gas spaces provide a pathway for oxygen transport from shoots to roots. Development of gas spaces in many wetland species is constitutive because this process occurs whether or not plants are growing in aerated or waterlogged soils (Schussler 1997). No reports are available on space occupied by aerenchyma in tolerant and susceptible rice varieties. Since this property is constitutive, it might provide a mechanism through which Fe-tolerant rice varieties could increase their root oxidizing power and improve their tolerance to Fe-toxicity.

Recent concepts on mechanism of Fe uptake by plants

There are two distinct iron uptake mechanisms in plants. Strategy I plants include all dicots and non-graminaceous monocots. These plants respond to Fe-deficiency by decreasing rhizosphere pH and reducing sparingly soluble ferric iron at the root surface by membrane-resident ferric chelate reductase (Chaney et al. 1972. Strategy II plants are limited to graminaceous monocots, which would include rice. These plants release mugineic acid-family phytosiderophores to the rhizosphere, where they solubilise sparingly soluble iron by chelation. The chelated complex is then absorbed into the roots. Genes for the synthesis of phytosiderophores have been isolated from barley (Higuchi et al. 1999; Kobayashi et al. 2001; Okumura et al. 1994; Takahashi et al. 1999). The gene families for heavy metal transporters in plants are quite large (Mäser et al. 2001; Mills et al. 2003; Williams et al. 2000). They have different substrate specificity and are located in different organs and organelles**.** This diversity is necessary to provide the high and low affinity systems needed to cope with varying metal availability in the soil; to provide the specific requirements for transport at the different cellular and membranes of organells within the plant; and to respond to a variety of stress conditions (Hall and Williams 2003).

The gene family, Nramps (Natural resistance associated macrophage proteins) transports Mn^{2+}, Cu^{2+} and Fe^{2+}. ZIP family (ZRT, IRT-like proteins) transports Fe^{2+}, Zn^{2+} and Mn^{2+}. ABC (ATP-binding cassette) transporters carry Mn^{2+} and Fe^{2+}. Most transitional metals are potential substrates for at least two gene families (Hall and

Williams 2003). Thus Fe and Mn are transported by both the Nramps and ZIPs. Mn is a substrate for both Ca^{2+}-ATPase and the cation/H^{+} antiporters. Zn is a substrate for both the CDFs (cation diffusion facilitator) and ZIPs. When a transporter protein is carrier for more than one ion a competition to occupy the substrate sites is possible. Thus negative interactions between Fe^{2+} and Zn^{2+}, Fe^{2+} and Mn^{2+}, Mn^{2+} and Cu^{2+}, Mn^{2+} and Zn^{2+} are possible. While such genetic regulation mechanisms operate while nutrient ions are initially taken up by plants they are probably inactivated when toxic concentrations of ions accumulate within the plant.

Effects of iron toxicity on plants

Heavy metals cause toxicity in plants due to production of reactive oxygen species by auto-oxidation and Fenton reaction (Fe^{++}+H_2O_2=Fe^{+++}+OH`+OH^-); this reaction is typical for transition metals such as iron or copper (Hall and Williams 2003). Under conditions of Fe toxicity, Fe^{++} iron accumulates in the apoplast of tissues and it is oxidized to Fe^{+++} through Fenton reaction. The production of hydroxy radical causes oxidative injury, which cannot be controlled by antioxidants. According to Xinxiang and Yamauchi (1995) leaf bronzing is caused by precipitation and deposition of ferric compounds in the apoplast. Oxidation of Fe^{++} to Fe^{+++} in the apoplast may result in increased production of free radicals such as O_2^- and HO^-, which may damage membrane, nick DNA, inactivate enzymes and proteins, and break up cellular integrity. There is a significant correlation between bronzing and ethylene production in leaves. However ethylene production did not increase with the increase of iron concentration in rice plants with intact roots. In iron toxic soils due to fast accumulation of Fe^{++} the exclusion capacity of apoplast is overcome and Fe^{++} enters the symplast. Then bronzing symptoms, injury to symplast and ethylene production takes place in parallel though not simultaneously.

Defense mechanisms by plants for metal detoxification

There are cellular mechanisms for metal detoxification and tolerance by higher plants. These are: Restriction of metal movements to roots; binding to cell wall and root exudates; reduced influx across plasma membrane; active efflux into apoplast; chelation in cytosol by various ligands; repair and protection of plasma membrane under stress conditions; transport of phytochelatin-metal complex into the vacuole and transport and accumulation of metals in the vacuole. Upon exposure to heavy metals, plants often synthesize a set of diverse metabolites that accumulate in the mM range, such as amino acids: proline and histidine, peptides: glutathione and phyto-chelatins (PC), and the amines: spermine, spermidine, putrescine, nicotianamine, and mugineic acids. These metabolites bear functional significance in the context of metal stress tolerance. Tseng et al. (1993) showed

that, in rice, both heat stress and heavy-metal stress increased the levels of mRNAs for low molecular mass HSPs (Heat shock proteins) of 16–20 kDa. HSPS act as molecular chaperones in normal protein folding and assembly, but may also function in the protection and repair of proteins under stress conditions.

Recent concepts on genetic regulation of K^+ uptake

Genetic regulation of potassium uptake by plants under normal conditions as well as under conditions of stress has been extensively reviewed (Mitra 2009; Navarro and Rubio 2006). K-transporters have been recently classified (TC- system) into two major pathways for K^+ acquisition by plants (Busch and Saier 2002; Mitra, 2008; Mitra, 2009). Class-I: Channels and other low affinity systems (LATS) effective at K^+ concentrations near 1 mM and above. There are three families, Shaker type channels, KCO channels and Cyclic-nucleotide-gated channels. Class-II: High affinity systems (HATS), operative at K^+ concentrations in the micro molar range. These consist of TrK/HKT transporters, [Na^+/ K^+ symporter], KUP/HAK/KT transporters, K^+/ H^+ antiporter homologue and Glutamate receptors. These genes have been identified in many plants including rice and have different roles in uptake of K^+ from soil solution present at either high or low concentrations. For example, Plant voltage gated Shaker channels participate at the cell and whole plant levels, in K^+ uptake from the soil solution, long-distance K^+ transport in the xylem and phloem and K^+ fluxes in guard cells during stomatal movement (Chérel 2004). In rice OsHKT1, a high affinity K^+ transporter showed properties of a Na^+ selective uniporter. A salt tolerant cultivar Pokkali contained OsHKT2, a K^+/Na^+ symporter (Golldack et al. 2003). The presence of many of these genes in plants and the functions of corresponding protein transporters coded by them are yet to be discovered.

The protective action of potassium on plants under stress at biochemical level has been well documented. Possible injury to plants under conditions of stress is counteracted by controlling acivity of super oxide dismutase, mitigating injury caused by free radicals of active oxygen. It maintains integrity of plasma membrane and thus protects the symplast from possible injury from Fe accumulation in the apoplast (Li 2006). Potassium increases proline content of leaves and suppresses malondialdehyde (MDA) content produced under stress and strengthens stress resistance crops. It also maintains the balance of internal hormone level of CTK, ABA and ethylene. Gating properties of K^+ channels and their expression are probably regulated by ABA (Roberts and Snowman 2000).

Amelioration of iron toxicity through application of K

In a green house experiment the effects of Fe, K and interaction between Fe and K, were all found to be significant. At 50 mg kg^{-1} of Fe application dry matter yield increased with increased levels of K application. As Fe level was increased to 100 mg kg^{-1} there was decline in dry matter yield at all levels of K. Increased levels of K applications increased dry matter yield significantly up to 60 mg kg^{-1}. Beyond 100 mg kg^{-1}, the yield reductions were drastic due to Fe-toxicity. Application of K significantly increased dry matter yield up to 200 mg kg^{-1} Fe application. Above this level yield differences were not significant (Table 6).

Table 6 Effects of Fe-K interaction on dry matter yields (g pot^{-1}) of rice (cv. Daya)

Fe levels (mg kg^{-1})	Levels of K (mg kg^{-1})			
	0	30	60	90
0	7.86	7.05	7.89	7.88
50	7.95	8.00	8.16	8.20
100	5.75	6.27	6.75	6.79
200	1.05	1.54	2.00	2.10
300	0.99	1.05	1.07	1.21
400	0.80	0.56	0.60	0.61
CD (0.05)	Fe	K	Fe x K	
	0.18	0.15	0.36	

Source: Sahu and Mitra 1992

Effects of Fe and K applications were significant on uptake of K (Table 7). The application of Fe at 100 mg kg^{-1} or above significantly decreased K uptake by rice. The application of K at higher doses increased K uptake significantly up to Fe level of 200 mg kg^{-1}. Above this level of Fe the effects were not significant.

Table 7 Effects of Fe-K interaction on K uptake (mg pot^{-1}) by rice (cv. Daya)

Fe levels (mg kg^{-1})	Levels of K (mg kg^{-1})			
	K_0	K_{30}	K_{60}	K_{90}
0	151.3	155.3	156.8	168.6
50	150.0	153.0	153.0	162.0
100	99.8	108.8	120.5	124.5
200	15.8	23.5	32.5	35.1
300	13.0	15.5	16.0	18.4
400	10.4	7.2	8.6	8.7
C.D(0.05)	Fe	K	FeXK	
	4.96	4.05	N.S	

Source: Sahu and Mitra 1992

Potassium and symptoms of iron toxicity, grain yield and quality

The effect of increased K application on leaf bronzing at 40 DAT (days after transplanting) was more for Jaya (susceptible to Fe toxicity) than for Mahsuri (tolerant). The decrease of bronzing due to increased application of K was steeper in Jaya but gradual in Mahsuri (Table 8). The grain yield of the susceptible rice variety Jaya increased with increase in K application and more than doubled at 120 and 160 kg K_2O ha^{-1}. The yields of tolerant variety Mahsuri also increased substantially with application of 120 and 160 kg K_2O ha^{-1}. The beneficial effects of higher doses of potassium on crop yield manifested, only in the presence of adequate quantities of other nutrients. Percent filled grains increased significantly with increased levels of potash for both the varieties. The susceptible variety (Jaya) benefited more than the tolerant variety (Mahsuri). This is due to alleviation of Fe toxicity by potassium and its known role in improving translocation of carbohydrates.

Table 8 Effects of potash application on iron toxicity score (leaves at 40 DAT), grain yield and quality parameter of rice grown on an iron toxic soil

Levels of K_2O (kg ha^{-1})	Iron toxicity score (1-9 scale)		Grain Yield. (q ha^{-1})		Filled grains (%)		Tinged grains (%)	
	Jaya	Mahsuri	Jaya	Mahsuri	Jaya	Mahsuri	Jaya	Mahsuri
0	8.3	2.7	10.3	18.2	62.3	82.9	14.7	7.5
40	7.0	2.3	13.8	22.1	65.0	84.4	11.1	6.3
80	5.0	1.7	19.4	22.7	71.6	85.2	10.1	5.3
120	5.0	1.0	22.1	26.8	76.8	86.0	9.4	4.7
160	3.0	1.0	24.4	28.8	78.7	87.1	8.5	2.7

	Grain Yield K	Grain Yield V	Grain Yield Kx V	Filled grains K	Filled grains V	Filled grains Kx V	Tinged grains K	Tinged grains V	Tinged grains Kx V
C.D (0.05)	3.12	9.43	N.S	8.79	7.47	7.47	2.42	1.56	N.S

Source: Sahoo 1989

In iron toxic soils apart from leaf bronzing the seed coat (husk) of rough rice develops brown spots, which fetches less price in the market. Potassium application significantly reduced percent tinged grains in both the varieties, more in Jaya than Mahsuri. About that 77% of iron taken up by the whole grain is retained in the husk and only 23% goes to the grain. This appears to be a natural mechanism in plants to protect its reproductive part from toxic constituents. During the process of grain filling most of the iron translocated to grains is filtered, retained by the husk and only a small portion reaches the kernel.

K, and Fe contents at different stages of growth

The K contents of the plants of both the varieties increased with increased levels of K. The K contents of Mahsuri (tolerant to Fe-toxicity) were higher than those of Jaya (suceptible) for all the levels of K at maximum tillering stage. At PI stage, this trend was reversed and K contents of Jaya were higher than those of Mahsuri. This reverse trend persisted at the harvest stage as well. The variety Jaya was benefited more than Mahsuri at higher doses of K (120 and 160 kg ha^{-1}) and its yield increased, more than two times the control yield. Fe-contents of both the rice varieties decreased significantly with increase in K-levels at all the stages of growth. Jaya had higher content of Fe than Mahsuri at every stages of growth. The tolerant variety Mahsuri had probably a constitutive mechanism (higher % of aerenchyma in the root cortex?) to exclude Fe uptake by increasing oxidizing power of its roots.

Conclusions

The lateral flow of soluble iron during rainy season enriched the soils to a toxic level. There is a considerable nutrient imbalance in the soil. There was a huge negative balance (-241.87 thousand tons annually) of K in the soil. The rice plants may not show the characteristic visual symptom of bronzing of leaves. Nevertheless a relatively higher Fe content of soil at sub-toxic level is probably responsible for low yield of rice and other crops of Orissa. Amendment of such soils with application of higher doses of K is essential and current recommended dose of K for rice be revised from 30 kg to 60 K_2O ha^{-1}. The ameliorating effect of applied K at higher doses on iron toxicity has been attributed to its role in increasing root oxidizing power in rice, which results in oxidation of Fe^{2+} to Fe^{3+} and its exclusion from uptake. This is evident from increase in intensity of iron oxide coating on rice roots at higher levels of K application. Recent concepts about genetic control of ion uptake do not indicate any common transporters for K and Fe. The mechanisms of their uptakes are unique to each of them. At ionic level there is no possibility for competition of Fe and K for the same site on any transporter protein. The effects of K on alleviating Fe-toxicity are indirect. K counteracts the toxic effects of Fe-toxicity by neutralizing them through different mechanisms and restoring the nutrient balance in the plants.

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Role of nutrient management in reduction of greenhouse gases

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Abstract Food, fiber, and fuel demands of a growing global population are resulting in increased fertilizer nitrogen (N) use. Farmers are being asked to improve N use efficiency and effectiveness through better management in their fields, to minimize greenhouse gas (GHG) emissions that contribute to climate change. Correct decisions in the management of N, which are based on sound agronomic and environmental research, can improve crop production and help reduce GHG emissions. Appropriate nutrient management helps increase biomass production necessary to help restore and maintain soil organic carbon (SOC) levels, which are necessary for sustainable production. Residual levels of soil nitrate and emissions of nitrous oxide (N_2O) may be minimized when best management practices (BMPs) for fertilizer N are implemented. Balanced fertilization with other essential nutrients enhances crop N use efficiency and is considered a BMP. Emissions of N_2O vary among fertilizer N sources, depending on site- and weather-specific conditions, and the cropping system. With intensive crop management, GHG emissions are not necessarily increased per unit of crop or food production. Such ecological intensification of crop production can help spare natural areas from conversion to cropland and allow conversion of selected lands to forests for GHG mitigation. Use of the right source, at the right rate, right time, and right place – termed 4R Nutrient Stewardship - is advocated, in combination with appropriate cropping and tillage practices, to achieve agronomic, economic, and environmental goals.

Keywords Best management practice (BMP) • carbon dioxide • climate change • cropping system • fertilizer • global warming • greenhouse gas (GHG) • nitrogen • nitrous oxide • methane

Introduction

Agricultural activities contributed 32 percent (13,360 million tonnes or Tg) of the

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global 41,382 million tonnes (Tg) of carbon dioxide (CO_2)-equivalent greenhouse gas (GHG) emissions in 2000; 63 percent of agriculture's GHGs were non-CO_2 GHGs (EPA 2006). Baumert et al. (2005) reported that about 15 percent of the world's GHGs were associated with agricultural activities in 2004, while Smith et al. (2007) estimated that agriculture contributed 10-12 percent of global anthropogenic GHG emissions in 2005. Among all economic sectors in developed countries, agriculture is generally a relatively small contributor to total GHG emissions, but the percentage contributions may be higher in many developing countries. The agricultural sector accounted for less than 7 percent (~413 Tg CO_2 -equivalent) of national GHG emissions in the United States (U.S.) in 2007 (EPA 2009), while the agricultural sector accounted for 24 percent (~ 412 Tg CO_2 -equivalent) of India's GHG emissions in 2005 (Garg et al. 2006).

Carbon dioxide (CO_2) dominates the CO_2-equivalent global GHG emissions from all sectors at 77 percent, while CH_4 emissions represent 15 percent and N_2O emissions represent 8 percent (EPA 2006). Countries with the largest portion of the global agricultural sector GHG emissions in 2000 were: China-18 percent, India-11 percent, EU-9 percent, U.S. -9 percent, and Brazil-8 percent (Baumert et al. 2005). Soil management activities were thought to contribute 40 percent of the global agricultural sector GHGs, with an even division (45-46 percent each) between nitrous oxide (N_2O) and methane (CH_4) emissions, on a CO_2 -equivalent basis (Baumert et al. 2005).

Emissions of the three prominent GHGs - CO_2, CH_4, and N_2O – are known to vary, depending on the land use and management (Bellarby et al. 2008). These three GHGs also differ in their effectiveness in trapping heat and in their turnover rates in the atmosphere. For a 100-year timeframe, unit masses of CH_4 and N_2O are considered to have 23 and 296 times the global warming potential (GWP), respectively, as a unit of CO_2 (IPCC 2001). Although older sources (IPCC 1996) may use the GWP CO_2 equivalent values of 21 for CH_4 and 310 for N_2O, for the purposes of this review we will use the more recent values of 23 and 296, respectively (IPCC 2001).

GHG mitigation by agriculture

An estimated 20 percent of GHG emissions are thought to be due to clearing and burning of forests, largely as a result of development pressures and human demand for food and fuel (Baumert et al. 2005). Safe-guarding and storing carbon (C) in agricultural systems is one means of mitigating GHG emissions. Increasing the agricultural productivity per unit of existing land area can help preserve and protect natural areas (Cassman 1999) and help minimize anthropogenic CO_2 emissions. Intensification of agricultural production on existing lands may also

lower the risk of accelerated N_2O emissions be preventing heightened decomposition of soil organic matter and subsequent N mineralization which may be associated with cultivation of former wetlands, forests, or grasslands (IPCC 2006). There is evidence that net GHG emissions can be kept low in agricultural cropping systems with optimized management that exploits the realistic, attainable yield potential (Adviento-Borbe et al. 2007). Intensive crop management systems may have increased GHG emissions per unit land area, but they do not necessarily increase GHG emissions per unit of crop or food production (Snyder et al. 2007; 2009). Using the economic optimum N rate (EONR) for crop production might increase emissions of CO_2 compared to a no N or 50 percent of the EONR scenario, but the increased land area that would be required to compensate for the yield loss under these two lower input scenarios would result in CO_2 emissions as much as four times greater than those of the intensive EONR system (Brentrup and Palliere 2008).

Soil organic carbon (SOC) sequestration is believed to be a cost-effective strategy for mitigating climate change through the first three decades of the 21st century (Lal 2003). Making agriculture C neutral by 2030 has been proposed as a challenging, but achievable goal (Trumper et al. 2009). Indeed, agriculture is increasingly being viewed as a solution rather than a cause of environmental challenges like global warming and climate change (Lal 2007; 2008).

Carbon loss (i.e. CO_2 emissions) in agricultural systems can be reduced in many ways, including the use of conservation tillage practices, use of appropriate cropping systems and rotations, integrated nutrient management, integrated pest management, and improved grazing land management (Lal 2008). Integrated nutrient management "conserves carbon while sustaining food production", " will depend on the specific characteristics of the agricultural system in question", and "can represent a win-win situation as high levels of soil organic carbon improve nutrient and water use efficiency, reduce nutrient loss and subsequently increase crop production" (Trumper et al. 2009).

Agricultural-related GHG emissions are a growing concern because there is an increasing global demand for food, feed, fiber, and fuel (Bellarby et al. 2008; EPA 2006). Coarse grains - including maize or corn (Zea mays L.), wheat (Triticum aestivum L.), and rice (Oryza sativa L.) - are the cereal crops with the largest global production and the greatest global demand (FAO, 2009); they provide over 60 percent of the world's human calories, either directly as food or indirectly through livestock products (Cassman et al. 2002). For most upland crops (e.g. wheat and maize), N_2O may be considered the principal GHG (Snyder et al. 2009), while CH_4 may be the GHG emitted in the largest amounts by flooded rice systems (Anand et al. 2005; Majumdar 2005). Since CH_4 and N_2O have GWPs so much higher than CO_2, agricultural management that reduces the emissions of these two GHGs is likely to have a large mitigation potential.

A number of studies have shown higher denitrification losses of N under reduced tillage or no-till conservation practices compared to plowed or frequently tilled soils, which have been attributed to higher available soil C (water soluble and mineralizable C), increased soil moisture, and higher microbial biomass under reduced tillage or no-till conditions (Coyne 2008). Efforts to address global increases in CO_2 emissions and to reduce soil erosion through conservation tillage practices (esp. no-till) and sequester more C in soil organic matter, must be considered cautiously and should be thoroughly evaluated because of the potential for increased risks for NO_3^- leaching (Phillips et al. 1980) and elevated N_2O emissions. The literature indicates mixed effects of tillage practices on NO_3^- leaching (Power et al. 2001); yet, Randall and Mulla (2001) reported no significant differences in NO_3^- leaching between no-till and tilled systems and Brye et al. (2001) found only slightly higher NO_3^- leaching in no-till compared to chisel-plowed agroecosystems. There are reports that N_2O loss under no-till were equal to or lower than those under intense tillage (Venterea et al. 2005), or were reduced during the growing season under no-till compared to conventional till (plowed), when averaged across years and four N rates (Halvorson et al. 2008). In contrast, Rochette et al. (2008) observed higher N_2O emissions with no-till compared to conventional moldboard plowing on a clayey soil (77 percent clay) in eastern Canada. More research is needed to simultaneously measure N_2O, CH_4, and CO_2 associated with different long-term tillage and nutrient management practices, under different climatic and cropping conditions.

Methane emissions and rice paddy management

Methane is emitted through methanogenesis under anaerobic conditions in soils and manure storage, through enteric fermentation, and during incomplete combustion while burning organic matter (IPCC 2006). Baumert et al. (2005) estimated that CH_4 emissions from livestock contributed 27 percent, rice cultivation contributed 10 percent, and manure management contributed 7 percent of the total global CO_2 -equivalent GHG emissions from agriculture. Rice cultivation contributed about 23 percent of all global CH_4 emissions from all sectors. Yan et al. (2009) estimated that more than half of the global CH_4 emissions were from rice fields in China and India. According to Garg et al. (2006), the agricultural sector contributed 83 percent of India's CH_4 emissions; rice cultivation was estimated to account for about 20 percent of the CH_4 emissions from the agricultural sector. The IPCC (2006) reported a default emission factor of 1.30 kg CH_4 ha^{-1} day^{-1} for flooded rice culture, with an error range of -0.5 to +0.9 (0.80 - 2.20). Methane emissions from a given area of rice are known to vary

considerably with the number and duration of crops grown, water regimes before and during the cultivation period, types and amount of organic and inorganic soil amendments, as well as soil type, temperature, redox potential, and rice cultivar (IPCC 2006; Xie et al. 2009).

About 80 percent of the world's harvested rice area is lowland or irrigated rice, and accounts for about 92 percent of the total rice production (Dobermann and Fairhurst 2000). Using the IPCC guidelines for 2006, Yan et al. (2009) estimated that CH_4 emissions could be reduced by 16 percent if all the continuously-flooded rice fields were drained at least once during the growing season, or if rice straw applications were made to fields in the off-season. If implemented together, these two management actions were estimated to reduce CH_4 emissions from rice fields by 32 percent. If alternate draining and flooding management does not require intensified N management practices, and it improves RE_N without impacting rice yield as was reported by Cabangon et al. (2004), it may offer practical CH_4 and N_2O emission reduction benefits. However, Johnson-Beebout et al. (2008) concluded that simultaneous minimization of both CH_4 and N_2O emission in soils growing rice (i.e. maintaining the theoretical redox potential between -100mV and 200mV) was not practically attainable because the redox potential changed with depth, but appropriate water and residue management could help reduce GHG emissions. Continuous flooding without crop residue incorporation had the lowest combined risk of CH_4 and N_2O emissions, but when residue was incorporated, alternate flooding and draining had similar or lower emission risks. Although draining continuously-flooded rice fields once per season would increase N_2O emissions, Yan et al. (2009) estimated that the increased N_2O emissions (assuming an average fertilizer N application rate of 150 kg N ha^{-1}) would only be approximately 2.7 percent of the reduced GWP resulting from the benefits of reduced CH_4 emissions.

Nitrous oxide emissions associated with nitrification and denitrification

Agricultural soils and their management – which includes the application of fertilizer and manure - are considered the principal global sources of N_2O emissions. Yet, N_2O emissions from agricultural soils represented only 3.5 percent of the total GHG emissions in North America in 2007, with little percentage change observed since 1990 (Environment Canada 2009; EPA 2009). Agricultural activities accounted for more than 80 percent of the total direct and indirect national N_2O emissions from all economic sectors in India in 2005, including approximately 60 percent from the use of fertilizer (Garg et al. 2006). Fertilizer N use and applications in 2007 accounted for 47 percent of the direct N_2O emissions associated with agricultural soil management in Canada (Environment Canada

2009), 28 percent in the U.S. (EPA 2009), and 27 percent in Europe's EU-15 (EEA 2009).

The interaction of soil factors that control nitrification and denitrification are complex and have a strong influence on the N cycle, and pathways that govern the direct and indirect risks for N_2O emissions. The amount of N_2O produced depends on the range of oxygen (O_2) concentrations in the soil, which is influenced by the moisture content, and temperature determines the rate at which the soil microorganisms nitrify or denitrify. The rate of N species conversion is slow at cooler temperatures, but increases to a maximum as temperatures rise. Other important factors, which affect N_2O emissions, are soil texture, the amount of ammonium (NH_4^+) available for nitrification, and the amount of nitrate (NO_3^-) available for denitrification (Firestone 1982; Granli and Bøckman 1994).

Nitrification requires ammonium NH_4^+, O_2, and CO_2 while denitrification is favored by a supply of NO_3^-, organic carbon (C), and reduced or O_2 deficient conditions (Rochette et al. 2000). Nitrification and denitrification, can occur simultaneously in soils and both can contribute to production of N_2O (Bremner and Blackmer 1978; Hutchinson and Davidson 1993). Denitrification occurs when NO_3^- is transformed to dinitrogen (N_2) gas as described in the following pathway, $NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$ (Firestone 1982; Firestone and Davidson1989; Robertson and Groffman 2007). The conversion of NO_3^- to N_2 can be complete, but a small and variable portion of the N is often emitted as N_2O gas. Emissions are sporadic, occurring before, during, and after the crop growing season. Increased levels of inorganic N and available C result in a greater abundance of denitrifying enzymes and may lead to increased denitrification rates. In soils with a low available C content, application of manure can result in greater N_2O emissions than with mineral fertilizer (Rochette et al. 2000). In well-aerated, moist soil conditions (>60% water-filled pore space) N_2O losses can be substantial (Coyne et al. 2008; Francis et al. 2008).

Increasing fertilizer N consumption and N_2O emission implications

Modern fertilizers are conservatively estimated to contribute to at least 30 to 50 percent of the world's food supply (Stewart et al. 2005). The Haber-Bosch synthesis of ammonia for fertilizer N production has made it possible to provide food for more than 40 percent of the world's population (Lal 2007; Smil 2002). While manures or organic manures have been a significant source of nutrients historically, their proportionate use for fertilizing crops is shrinking. In India for example, "The proportion of cattle manure available for fertilizing purposes decreased from 70 percent of the total produced in the early 1970s to 30 percent in the early 1990s" (FAO 2006).

Farmers, input providers, crop advisers, and governments are all seeking opportunities to improve the efficiency and effectiveness of fertilizer N use to maximize economic returns, to increase food production, to sustain productivity, and to minimize environmental consequences - including GHG emissions. Global fertilizer nitrogen (N) consumption has been increasing; especially in East Asia and in South Asia (Figure 1) (IFA Statistics 2009), and consumption among these countries is projected to increase into the near future (Figure 2) (FAO 2009).

Fig. 1 Global fertilizer N consumption (IFA Statistics 2009)

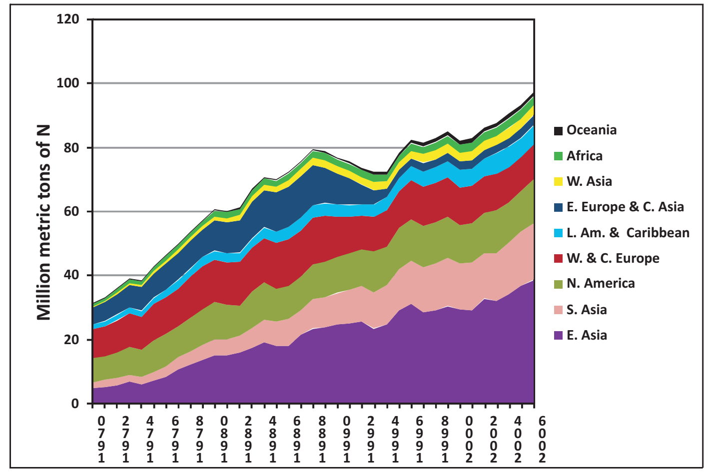
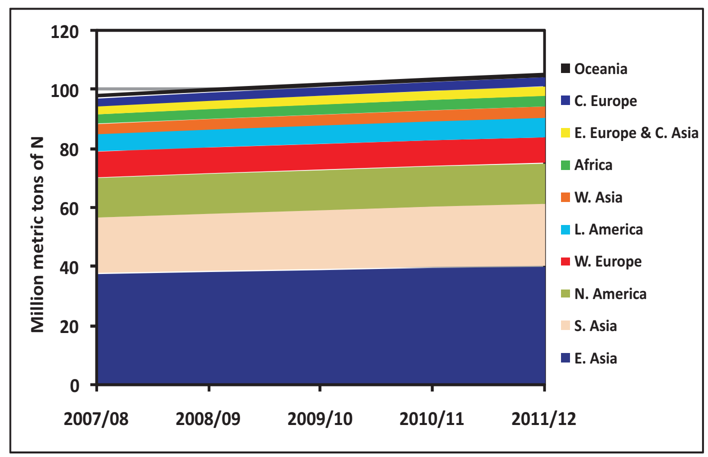


Fig. 2 Projected world fertilizer N consumption (FAO 2009)



Increased fertilizer N consumption has raised concerns about increases in reactive N release to the environment, cascading effects on the N cycle, and the associated direct and indirect N_2O emissions from a global perspective (Galloway et al. 2003, 2004; Sutton et al. 2007) and within an Asian and Indian context (Galloway et al. 2008). The role of nutrient management in minimizing environmental losses of reactive N, and the potential to help mitigate GHG emissions, may be of particular interest in China and India because they may presently contribute more than two-thirds of Asia's agricultural N_2O emissions (Singh and Singh 2008).

Fertilizer management for nutrient use efficiency and effectiveness

One of the key ways to reduce the risk of GHG emissions associated with fertilizer use and cropping systems is to increase nutrient use efficiency and effectiveness. Simply stated, good fertilizer stewardship (Roberts 2007) - applying the right fertilizer source, at the right rate, right time, and right place (i.e. 4R Nutrient Stewardship) - should lead to improved economic crop production and help minimize the environmental impacts; including minimization of GHG emissions. Implementation of fertilizer best management practices (BMPs) (Bruulsema et al. 2008; IFA 2007), adoption of 4R Nutrient Stewardship (Bruulsema et al. 2009) and Site-Specific Nutrient Management (SSNM) have been advanced as practical means to help achieve agronomic, economic, and environmental objectives (Adviento-Borbe et al. 2007; Dobermann and Fairhurst 2000; Dobermann and Cassman 2002; Fixen et al. 2005; Peng et al. 2003; Snyder 2008; Snyder et al. 2007, 2009; Vetsch et al. 1995).

Nitrogen from soil, fertilizer and manure sources is used relatively inefficiently by crops, with 50 percent or less N use efficiency (Balasubramanian et al. 2004), but N use efficiency can be increased to 60 to 70 percent or more with improved management in many cropping systems (Cassman et al. 2002; Kitchen and Goulding 2001; Raun and Johnson 1999). Based on available data in the U.S. and Asia, Dobermann and Cassman (2002) reported that typical on-farm apparent crop recovery of applied N (RE_N) was only 30 percent in rice and 37 percent in maize, but with good management RE_N could be 50 to 80 percent. Increasing crop RE_N can reduce the potential for losses of N that reduce economic returns to farmers and which raise the risks of environmental impact. In cereal crop research trials, total RE_N from a one-time application of N averages about 50 to 60 percent, and 40-50 percent under most on-farm conditions (Dobermann 2007). The remainder of N is subject to loss from the cropping system. Based on 241 site-years of field experiments in North America and China, Fixen et al. (2005) reported that first-year crop RE_N increased from 21 percent in the conventional or check treatments to 54 percent with site-specific, multi-element balanced nutrition. These results indicate there is a considerable opportunity to recover lost efficiencies through improved nutrient management, especially by emphasizing balanced and optimum levels of all nutrients.

It is possible for NO_3^- to accumulate in the soil whenever N is not the factor most limiting crop production. For example, in a long-term study on the North American Great Plains comparing maize response to N rates with and without P, adequate fertilization for improved crop nutrition increased yields 42 percent, improved economic returns, and reduced soil profile NO_3-N levels by 66 percent (Schlegel et al. 1996). Proper K nutrition, through adequate rates of fertilizer and maintenance of soil test K levels in the agronomic optimum range, can improve RE_N (Figure 3) and also reduce loss of NO_3^- (Johnson et al. 1997). High yield management research with maize in the state of Kansas in the U.S. (Gordon 2005) showed that balanced fertilization, using the right rate of other essential nutrients like sulfur (S) in addition to N, P, and K can significantly increase crop RE_N (Figure 4).

Aulakh and Malhi (2004) reported additional examples of the impacts of proper nutrient balance with N, and showed that improvements in RE_N ranging from approximately 20 to 50 percent were possible. Balanced fertilization and soil fertility are important major factors under farmer control, which affect crop yield and N use efficiency (Balasubramanian et al. 2004; Cassman et al. 2002; Snyder and Bruulsema 2007; Stewart et al. 2005). These examples of balanced fertilization underscore the need for farmers to optimize all other agronomic

Fig. 3 Effects of proper K fertilization on apparent N recovery by maize (Johnson et al. 1997)

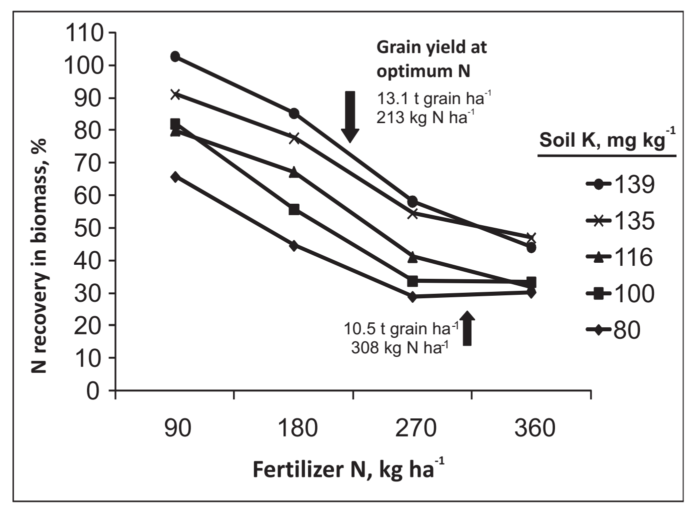
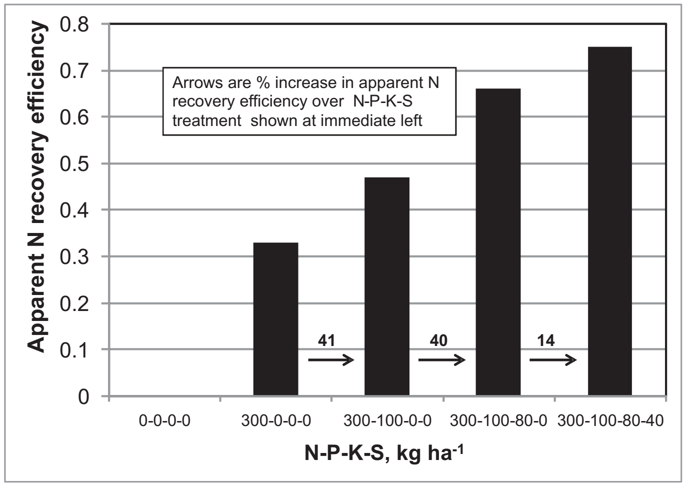


Fig. 4 Balanced fertilization effects on apparent N recovery by maize using balanced fertilization (assuming 25 kg of N uptake per ton of grain (Gordon 2005).



factors, to ensure that N provided to the cropping system is used as efficiently and effectively as possible; to prevent NO_3^- accumulation, leaching and drainage losses that could pose risks to water resources, and which could potentially result in increased N_2O emissions.

Nutrient imbalance and inadequate soil test levels of phosphorus (P) and potassium (K) are currently limiting crop production in many countries and regions (Table 1). In North America, 41 percent of the soil P tests and 39 percent of the soil K tests indicated that fertilizer should be applied each year to avoid profit loss by most major crops. Fifty-six percent of the soil P tests and 52 percent of the soil K tests indicated a need for fertilization rates of at least crop removal to sustain crop production, in support of typical "build-maintenance" recommendation programs (Fixen et al. 2005).

Nutrient management practices that improve RE_N of applied N are likely to minimize the risks of N loss via the various loss pathways (immobilization, ammonia volatilization, runoff, leaching, denitrification) (Chien et al. 2009). Nutrient managers should consider the risks for reductions in N loss via one pathway being offset by increased N loss via another pathway (Snyder 2008; Snyder et al. 2009). For example, reductions in the direct loss of N via ammonia (NH_3) volatilization, could conserve N and increase the inorganic soil N supply and lead to an increased risk for elevated NO_3^- in water resources; which may elevate the potential for direct and indirect N_2O emissions (Crutzen et al. 2008; Del Grosso et al. 2006; Galloway et al. 2003; Sutton et al. 2007). The combination of

Table 1 Phosphorus (P) and potassium (K) fertility condition of sampled soils in the U.S., China, and India and median soil test levels in North America (adapted from Fixen et al. 2005)

	Plant available soil P			Plant available soil K		
Level	U.S.	China	India	U.S.	China	India
	% of soil samples			% of soil samples		
Low	24	46	46	14	58	13
Medium	23	25	49	29	18	53
High	53	29	5	57	23	34

North America[a]			
	Median soil test P (mg kg^{-1})		Median soil test K (mg kg^{-1})
2001	27		154
2005	31		154
% of soil samples with < 25 mg kg^{-1} soil test P in 2005	42	% of soil samples with < 160 mg kg^{-1} soil test K in 2005	53

[a]Data source: PPI/PPIC/FAR 2005.

fertilizer source, timing and placement that produces the greatest yield with the least amount of N is likely to help optimize agronomic goals and minimize environmental impacts. Continued in-field assessment of new practices for optimum crop N use efficiency, and measurements to assess progress, are essential to production and environmental goals (Dobermann 2007; Snyder and Bruulsema 2007).

Fertilizer N management for reduced methane emissions

There is conflicting information in the literature on the effects of fertilizer N management on CH_4 emissions. The presence of rice plants under flooded culture and the type of fertilizer N applied were reported to affect the emissions of CH_4, N_2O, and N_2 (Lindau et al. 1990). Application of ammonium–based fertilizers (e.g. urea, ammonium sulfate) can increase rice growth and stimulate plant-related CH_4 emissions, but this enhanced emission may be countered by ammonium effects on the inhibition of CH_4 oxidation (Xie et al. 2009). Literature reports of inhibitory and stimulatory effects of ammonium fertilizers on CH_4 emissions were mentioned in a report of work with maize and soybean (*Glycine max* L.) in the eastern U.S. cornbelt (Hernandez-Ramirez et al. 2009), which indicated CH_4 was absorbed by soils receiving fertilizer N application (urea ammonium nitrate or UAN) while manured soils emitted CH_4. In China, increasing the ammonium N rates from medium to high levels, within the range of typical N rates in China, did not appear to modify CH_4 emissions (Nayak et al. 2007). Methane oxidation was stimulated by fertilizer or compost N, but when applied together CH_4 oxidation was inhibited (Nayak et al. 2007). Bufogle et al. (1998) cited work in which CH_4 emissions were less when ammonium sulfate was the fertilizer N source for rice, as opposed to urea, which is in agreement with a review by Cai et al. (2007).

When flooded soils become more reduced (more negative redox potential), sulfate–reducing bacteria effectively compete with methanogenic bacteria. Although NO_3-based fertilizers can reduce CH_4 emissions (Hou et al. 2000), by temporarily increasing the redox potential (Jugsujinda et al. 1995), they are rarely applied and generally not practical for mitigation of CH_4 emissions in rice fields because of their low N use efficiency and stimulation of N_2O emissions (Cai et al. 2007). To better evaluate the relationship between N management and CH_4 emissions, Cai et al. (2007) suggested more research is needed at moderate N levels (<150 kg ha^{-1}) with different types of N fertilizers, different application times, and different rice cultivars.

Fertilizer management for reduced nitrous oxide emissions

Right source

Snyder et al. (2009) reviewed the available data on the effects of N source, rate, timing, and placement in combination with other cropping and tillage practices, on GHG emissions. Their review included summaries of information in three reviews published in 1990, 1994, and 2006, which evaluated the effects of fertilizer N source on direct soil N_2O emissions. In numerous studies, which had been reviewed by Bouwman et al. (2002a; 2002b), N_2O emissions appeared lower for NO_3-based fertilizers compared to NH_4-based fertilizers, or organic or synthetic-organic sources. A later report by Stehfest and Bouwman (2006) indicated that differences among fertilizer types almost disappeared, after balancing for rate of application, crop type, climate, SOC, soil pH, and length of experiment (Table 2). Bouwman et al. (2002b) warned against applying any of the estimates from their summarized data to individual fields because their emission estimates represented gross relative differences among fertilizer sources/types.

In contrast to the global summaries and modeling approaches mentioned above, Chen et al. (2008) stated, "Since ammonia or ammonium producing compounds are the main sources of fertilizer N, maintenance of the applied N in the ammonical form should result in lowered emissions of nitrous oxide from soils". Harrison and Webb (2001) also reported that relative N_2O emissions from NO_3-based sources may be greater than those from NH_4-based sources and

Table 2 Summary of N_2O emissions induced by common fertilizer N sources, based on Bouwman et al. (2002a; 2002b) and Stehfest and Bouwman

N source	Mean fertilizer induced emission[1]		Balanced median emission[2]	
	n	N_2O as % of applied N	n	kg N_2O -N ha^{-1}
Calcium ammonium nitrate	61	0.7	73	1.56a[3]
Ammonium nitrate	59	0.8	131	1.12a
Anhydrous ammonia	38	0.9	38	1.04a
Nitrate-based fertilizers[4]	53	0.9	53	0.80b
Urea ammonium nitrate (solutions)	37	1.0	40	0.78b
Urea	98	1.1	131	0.96b
Ammonium-based fertilizers[5]	59	1.2	74	0.82b
IPCC default		*1*		

[1] Bouwman et al. 2002a, 2002b
[2] Stehfest and Bouwman 2006
[3] Values followed by a common letter are not significantly different, based on two-tailed statistical tests (Stehfest and Bouwman 2006)
[4] Includes potassium nitrate, calcium nitrate, sodium nitrate (Bouwman et al. 2002a; 2002b)
[5] Includes ammonium bicarbonate, ammonium chloride, ammonium sulfate (Bouwman et al. 2002a; 2002b)

differences may increase with increasing soil wetness. Higher N_2O emissions with NH_4-based fertilizers may be related to potential NO_2^- accumulation or N_2O production during nitrification (Venterea and Stenanas 2008). These conflicting reports and the summary by Snyder et al. (2009) raise questions about the importance of N source in addressing N_2O emissions, and they illustrate the need for continued research.

Intuitively, one might expect a potentially higher N_2O loss with an abundance of NO_3-N in soil systems from NO_3-based fertilizers compared to other N fertilizers, since NO_3^- and NO_2^- are essential for denitrification (Coyne 2008). However, higher N_2O emissions with anhydrous NH_3 were found in several studies which compared it with other N sources (Breitenbeck and Bremner, 1986; Venterea et al. 2005). In contrast, Burton et al. (2008) found no differences in N_2O emissions between anhydrous ammonia and urea in Manitoba, Canada. It is possible that fertilizer source/type effects on N_2O emissions may be less important than the size of the mineral N pool, and the warm, moist soil conditions which are conducive to rapid nitrification and denitrification. For example, Mosier et al. (1996) considered soil management and cropping systems as having more impact on N_2O emissions than mineral N source.

Right rate

Merely cutting applied N rates to reduce the potential for increases in residual soil NO_3-N was not considered an appropriate management action because N rates below the EONR could result in "mining" of soil organic nitrogen (SON) and cause a decline in long-term soil productivity (Jaynes and Karlen 2005). Nitrogen rates considerably above the EONR may raise the risk of NO_3^- leaching and increase the risk of direct N_2O emissions (Follett 2001), as noted in the review by Snyder et al. (2009). Fang et al. (2006) reported a significant potential to better manage N applications to increase N use efficiency and to reduce NO_3-N leaching in the North China Plain; especially since the actual N fertilizer application rates of 400–600 kg N ha^{-1} yr^{-1} by farmers exceeded the 200-300 kg N ha^{-1} yr^{-1} requirements for the wheat–maize rotation system. Rates of N above the EONR were associated with increased residual soil NO_3^- and greater potential for N loss in winter wheat production systems in the North China Plain (Cui et al. 2009). Similar results of elevated soil NO^-_3 with N rates above the EONR have been reported in the U.S. (Hong et al. 2007), and the authors suggested that additional environmental benefits may be possible with use of variable-rate N applications. High residual soil NO_3^-, if not properly considered in nutrient management planning, can result in reduced RE_N, increased soil NO_3^- accumulation and leaching below the root zone; especially where precipitation exceeds evapotranspiration (Follett 2001). When other factors are held constant, increased fertilizer N rates may increase soil NO_3^- accumulation and N_2O emissions (McSwiney and Robertson 2005). However, because soil moisture and temperature have such a strong influence on nitrification and denitrification, and because the level of crop management and crop yields may also exert an influence on soil N dynamics, N_2O emissions may not always exhibit a strong linear correlation with increases in soil NO_3^-, even at similar N input rates (Adviento-Borbe et al. 2007). As explained by Adviento-Borbe et al. (2007), N_2O emissions may be affected more by the soil N turnover rather than the mineral N pool size per se, which is in agreement with Mosier et al. (1996).

It is quite challenging to manage fertilizer N at an appropriate amount because each agro-ecosystem and specific growing season will differ as to what is most appropriate. Residual soil N estimation has proven useful in some regions, but wide ranges in yield response to a given N rate often occur when attempting to calibrate soil NO_3^- tests or mineralizable N tests (Dahnke and Johnson 1990; Follett 2001; Stanford 1982). A scatter or "cloud' of data points instead of a distinct response curve is often observed in research calibration efforts because of the large spatial and temporal variability in soil NO_3^- (Meisinger 1984). Nitrous oxide emissions began to increase significantly compared to unfertilized check treatments with N rates above 100 kg ha^{-1} in an irrigated corn study (Grant et al. 2006; Kachanoski et al. 2003). In the less humid areas of the world where upland crops predominate, farmers may minimize the potential for N_2O emissions by following a nutrient management plan (NMP) which includes soil testing to determine residual NO_3^- in the soil; where it is appropriate and has been properly calibrated by research. By considering the normal N mineralization potential from SOM for soils in a field and the residual soil NO_3^-, the deficit between the sum of these two N-inputs and the expected N uptake demand for realistically attainable crop yields can be calculated; which allows estimation of an appropriate amount of timely and well-placed N fertilizer.

Right time and right place

Shortening the time in which NH_4-based fertilizers can undergo nitrification or NO_3 –based fertilizers can be denitrified before plant N uptake, is likely to decrease N_2O emissions (Bouwman et al. 2002a). Timing of N applications to provide just what the plant needs, just when it needs it would be ideal. However, practical labor, economic, and logistical challenges often prevent such perfect N timing management in farmer fields. Complexities of weather uncertainty (IPNI 2007) and unpredictable soil N release necessitate some compromise in N management, and in the past, many farmers have preferred to apply N earlier than the plant needed it to avoid N deficiencies (Randall and Goss 2001). Some of these challenges in Asia are being met in rice production with the SSNM approach and use of leaf color charts, which are calibrated to identify in-season N needs (Dobermann and Fairhurst 2000; Fairhurst et al. 2007). In addition, technologies are being calibrated to sense crop N status and to adjust N fertilization on-the-go (Raun et al. 2002; Scharf and Lory 2009).

Particularly in humid environments, when N is applied on the soil surface and not incorporated, a substantial proportion can be lost to the air as NH_3; especially with manure or urea as sources (Follett 2001; Kissel 1988). For example, in drill-seeded flood-irrigated rice systems in the southern U.S., NH_3 volatilization can exceed 30 percent of the applied N if flooding is delayed for up to 14 days after urea is surface broadcast. Most of this NH_3 loss occurs within 7-10 days after N fertilization if flooding is delayed; immediate flooding after urea fertilization in dry-seeded flood-irrigated rice systems minimizes loss and optimizes RE_N (Griggs et al. 2007). In transplanted rice paddy systems in Asia, NH_3 volatilization losses have exceeded 50 percent of the applied urea N, in rice less than 3 weeks old after transplanting; peak losses occurred within 7-10 days after N application. Ammonia volatilization loss during panicle initiation was much less and ranged from 10-15 percent of the applied urea N (Buresh and Witt 2008).

Although it is not a GHG, volatilized NH_3 from fields will be ultimately deposited back on the soil or water resources elsewhere. Generally, the proportion of N emitted as N_2O is assumed to be the same, whether the applied N stays available in the soil for plant uptake or it goes elsewhere as NH_3. Therefore, BMPs that reduce NH_3 volatilization also reduce N_2O emission in the same proportion as the amount of N conserved. In lowland irrigated rice systems, NH_3 volatilization is a significant management issue, since Buresh and De Datta (1990) found that NH_3 volatilization, and not N_2O or N_2 emissions, was the dominant loss pathway for N applied as urea. Buresh and Witt (2008) reviewed many published studies on N transformations in submerged soils, and reported that soil incorporation of urea before transplanting, as opposed to broadcasting into the floodwater 10-21 d after rice transplanting, reduces NH_3 loss.

Urea placed in a band below and to the side of the seed-row resulted in lower N_2O emissions compared to urea broadcast on the soil surface, in 2 years of a 3-year study at two sites in Saskatchewan, Canada (Hultgreen and Leduc 2003). In many small grain cropping systems in the Great Plains area of North America, farmers subsurface place N and P fertilizers to enhance crop nutrient recovery and to increase yields.

According to Wang et al. (2007) the framework of SSNM helps ensure that essential N, P, and K are applied as needed by the rice crop, it eliminates nutrient wastage by preventing excessive rates of fertilization and it helps avoid fertilization when the crop does not need it. Using this same approach in the Phillipines and Vietnam, in comparison with typical farmer practice, it was shown that N_2O emissions (modeled) and CO_2 - equivalent GHG emissions could be reduced through improved fertilizer use efficiency (Pampolino et al. 2007). In environments where higher yield could be attained with less fertilizer N, lower N_2O emission per unit of grain yield could also be achieved. Farmer profits were increased with SSNM by 34 U.S. \$ ha^{-1} $year^{-1}$ in Vietnam, 106 U.S. \$ ha^{-1} $year^{-1}$ in the Philippines, and 168 U.S. \$ ha^{-1} $year^{-1}$ in India (Pampolino et al. 2007). As a consequence of these intensive cropping system SSNM nutrient efforts in Asia, rice and wheat crop yields are being increased, RE_N is improving, use of indigenous soil N is being improved, and economic returns to farmers are being raised (Buresh and Witt 2008; Khurana et al. 2008).

Enhanced efficiency of fertilizers

Enhanced-efficiency N fertilizers (slow and controlled release fertilizers and stabilized N fertilizers) have been defined as products that minimize the potential of nutrient losses to the environment, as compared to "reference soluble" fertilizers. Enhanced efficiency fertilizers were divided into two general categories of; Slow-release and controlled-release, or encapsulated fertilizers and fertilizers with nitrification and urease inhibitors or stabilized fertilizers (Weiske 2006).

These product technologies may help some farmers reduce risks of N loss under conditions where management challenges limit RE_N optimization with the more "reference soluble" fertilizers, and where N losses pose significant economic and environmental costs. As Dobermann (2007) has stated, these technologies have some theoretical advantage over the more "knowledge-intensive" N management "because the knowledge is 'embedded' in the product to be applied", but the relative importance of these technologies may vary among cropping systems and regions. Such embedded knowledge, as experience has shown with seeds, can lead to high adoption rates by farmers, provided that the benefit/cost ratio is high (Dobermann 2007). More details on some of these enhanced efficiency technologies were provided in the review by Snyder et al. (2009), so only selected points will be made here regarding these fertilizer technologies.

Controlled-release technologies, by affecting the timing of N release from fertilizer (Shaviv 2000), have potential to reduce leaching losses of NO_3^-, volatile losses of N as NH_3, and N_2O emissions (Chien et al. 2009). Reductions in these losses may improve RE_N and provide greater stability in fertilizer N performance. Urease inhibitors can help reduce ammonia volatilization and nitrification inhibitors can help reduce the potential for accumulation of NO_3^- and losses via leaching and denitrification. Use of the nitrification inhibitor dicyandiamide (DCD) and polyolefin coated urea (POCU/CRF), when used with urea on a barley (Hordeum vulgare L.) field were capable of reducing N_2O emissions by 81 percent and 35 percent (Shoji et al. 2001). Average total N fertilizer losses from the common pathways (e.g. NH_3 volatilization, NO_3^- leaching, NO and N_2O emissions) in the study were 15 and 10 percent in the DCD and urea treatments, respectively, and only 1.9 percent in the POCU/CRF treatment. These results indicate RE_N may be improved with POCU/CRF and nitrification inhibitor technologies, and allow possible reductions in the total fertilizer N rate.

Halvorson et al. (2009a; 2009b) found that N source had little impact on irrigated maize grain yield, but did impact N_2O emissions. Inclusion of soybean or dry bean (Phaseolus vulgaris L.) in a no-till maize rotation increased the level of N_2O emissions during the maize year. Controlled release and stabilized N sources reduced N_2O emissions by 29-50 percent compared to UAN and urea, under a no-till continuous maize system. Use of slow or controlled-release fertilizers and the use of urease and nitrification inhibitors are not new to agriculture. However, there is renewed interest associated with increased fertilizer costs and a better understanding of the potential impacts of inefficient fertilizer N management. Measurement of environmental impact with enhanced efficiency fertilizers is an area of on-going research (Grant and Wu 2008; Halvorson et al. 2008; Motavalli et al. 2008). More enhanced efficiency fertilizers are becoming available to farmers, which may increase the ability to match specific fertilizer properties and characteristics with specific crop and soil system requirements.

Conclusions

Global agricultural growth will be necessary to meet human demands for food, fiber, and fuel. This growth is expected to depend on concomitant increases in fertilizer use. Because there are multiple economic, social, and ecological goals associated with increased crop production and fertilizer use, nutrient management planning will likely involve broader stakeholder input and more multi-disciplinary approaches than in the past. Science-based nutrient management principles should form the foundation of every nutrient input decision and goal: in developed and developing countries alike. The fertilizer industry is working globally with university researchers, extension leaders, government agencies, crop advisers, and leading farmers to implement a strategy of improved nutrient stewardship. This effort has been termed '4R Nutrient Stewardship' and depends upon use of the right nutrient source at the right rate, right time, and right place. Crop nutrient use efficiency can be improved through the '4R' approach to help raise global RE_N values for cereal crops from the typical <50 percent range to the 60-70 percent range, or higher. It is critical that efforts to increase nutrient use efficiency will simultaneously address improved nutrient effectiveness. Policies and action to reduce the GWP and to counter climate change through reduced GHG emissions must consider agriculture not only as a source of GHG emissions, but also as a solution. Land suitable for crop production is becoming more limited as a result of population-driven urban encroachment, and expanded commitments to preserve natural areas. The principal way to meet the expanding food, fiber and fuel production challenges, while addressing GHG emissions, is through ecological intensification of crop production on existing lands. Site-specific nutrient management will become increasingly important as a consequence of these pressures.

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Forest fertilization: Trends in knowledge and practice compared to agriculture

Philip J Smethurst

Abstract Plantation forestry continues to intensify and grow in area, with a concomitant increase in fertilizer demand. Virtually no fertilizer is used on non-plantation forest systems. The scale of fertilizer use per ha per year in a small proportion of plantation systems is now similar to some agricultural production systems, but the total area of plantation forestry remains only a few percent of that used for agriculture. Hence, in a global context, forestry is a minor user of fertilizers. In relation to the knowledge base for fertilizer management, forestry and agriculture have similar practical questions that drive research, i.e. nutritional diagnosis and the development of fertilizer prescriptions that optimize production, environmental and economic goals. Much of this research is soil-climate-species-management specific. During the past few decades, solution culture methods were developed that maintain stable internal nutrient concentrations, which were essential for improving our understanding of nutrient-growth relationships. The development of plant production models that include the mechanistic simulation of nutrient supply and uptake are at an early stage of development. Plantation forestry and agriculture lack a mechanistic basis for evaluating base cation availability that accounts for Al-pH-root interactions. Further developments in this field could assist in rationalizing the use of lime. There is a lack of resources available in plantation forestry, and probably also in agriculture in some countries, to develop and refine calibrations of traditional types of soil and foliar analyses. Further testing of soil solution approaches is warranted. Further research on resource use efficiency, wood quality, rhizosphere relations, and mixed-species systems in relation to fertilization is also warranted.

Keywords N-fixation • plantations • nutrients • soil testing • lime • rhizosphere

Introduction

Fertilizer use in forestry is almost entirely restricted to plantations, of which there

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were 140 Mha world-wide in 2005 when this land use was increasing by 2.8 Mha annually (FAO 2006). The plantation area is likely to continue to expand, and almost all plantations receive fertilizer at some stage of their development. Hence, an increasing area of plantations leads to an increase in the demand for fertilizers in forestry. Another factor driving increased fertilizer usage in forestry is the level of intensification of management, with the objective of increasing the average rate of wood production per unit of land. Intensification reduces the duration of the crop cycle and increases the frequency of harvesting, and, because younger trees have higher concentrations of nutrients, it increases the average rate of nutrient export.

Until about three decades ago forest plantations had a rotation cycle of at least two decades, which was many times longer than most agricultural crops, but increasing demand globally has intensified management and led to rotation lengths of 4- to 7-years in some countries for growing several *Eucalyptus* and *Acacia* species. Demand for wood for traditional uses (paper, sawn timber, veneers, charcoal and firewood) drove this intensification, and short-rotation tree crops are emerging as a possible option for producing bioenergy (Gopalakrishnan et al. 2009). Most perennial horticultural crops have much longer rotations than these short-rotation forest plantations. Therefore, in relation to annual fertilizer application requirements, many forest plantations can be considered broadly similar to annual or perennial agricultural crops. However, Asia and South America, where the shortest-rotation forest plantations are grown, together account for only 24% of industrial roundwood production globally (FAO 2005). Most roundwood is still produced in much longer rotations in Europe, North America and Oceania from natural forests and plantations.

Forest nutrition research can be considered to have begun with the first detailed publications by Ebermayer in 1876 and 1882 in Germany, when it was noted that the periodic removal of the forest litter layer for use as animal bedding led to unhealthy forests, and that this effect was nutritionally mediated (cited by Attiwill and Leeper 1987, Rennie 1955 and Tamm 1995). Since Ebermayer, forest nutrition research has bolstered general knowledge of soil-plant nutrient relations in synergy with developments in agriculture and other domains of plant nutrition. Agricultural research with artificial fertilizers began around 1842 when Lawes and Gilbert took out a patent on the production of superphosphate, and in the same year Lawes published the effects on cabbage growth of applying different forms of inorganic nitrogen fertilizers (Johnston 1994). Only a few years later in 1847, inorganic fertilizer experiments on forest soils commenced in France (Baule and Fricker 1970, cited by Pritchett 1979). However, forest fertilization commenced operationally for many plantation types only in the 1950s, after the development of reasonably sound scientific principles (Ballard 1984). The use of fertilizer in forestry increased during the 1960s and 1970s as the economic value of fertilization became apparent; fertilizing to maximize tree growth rate became a priority (Cromer et al. 1977; Schönau and Herbert 1989). As the need developed to refine the management of forest fertilization, which was mainly in a plantation context, forestry began to contribute generally to the science of fertilization.

The objective of this review is to provide an overview of fertilizer usage in forestry internationally and the history of forest nutrition research, and describe developments in specific aspects of the knowledge base of forest fertilization that have implications for other cropping systems. I conclude by identifying major knowledge gaps and likely future trends in the research and practice of forest fertilization.

Goals of fertilization

In agriculture, fertilizers can be used to increase vegetative growth and total biomass production, e.g. for root-crops and pastures, but most fertilizers are used to increase reproductive growth for food production, e.g. cereals, oilseeds, and horticulture. In addition to maximizing yields, fertilizers are managed in many instances to optimize product quality, which is achieved by synchronizing the rates and timing of fertilization with the stage of growth. In contrast, the main goal of fertilization in forestry is to increase biomass production for wood volume and weight (which is the main context of other sections of this review) whilst avoiding serious deteriorations in wood quality. On a small scale, fertilizers are also used in forestry to manage seed production (Williams et al. 2003).

Where it has been of interest, wood quality in relation to fertilization has mainly been assessed for pulp and paper purposes. The principle qualities of interest are wood density, fibre diameter and length, microfibril angle, cell wall thickness, and contents of lignin, cellulose and extractives. The high cost of assessing these attributes has hindered progress, but the use of NIR analyses has recently reduced the cost and increased research in this area. In relation to eucalypts, fertilizer generally either increases or has no effect on wood quality, but it increases the nutrient content of wood and hence nutrient export from sites (Raymond 1998). In conifers, fertilization that increases growth rates also tends to decrease wood density, but overall there is usually an increase in the total value of wood for sawn timber or pulpwood (Antony et al. 2009; Cao et al. 2008; Downes et al. 2002, Nyakuengama et al. 2002; Zobel 1992). Overuse of fertilizers in forestry can result in trees with multiple or contorted stems that greatly reduces the value of the tree for either pulpwood or sawn timber purpose (Turnbull et al. 1994).

Fertilizer use in forestry

Forest plantations are widespread around the globe, with large areas in suitable parts of Asia, the Americas, and Europe, and much smaller areas in Africa and Oceania (FAO 2006). World-wide, forest plantations grown for wood products occupy about 3% of the total land area used for food and fibre production. The same percentage applies to Australia, where the low percentage of land used for plantations compared to agriculture, combined with low average annual rates of fertilizer usage per ha, results in plantations accounting for only 0.12% of N and 0.24% of P fertilizer usage (May et al. 2009b).

While the proportion of total fertilizer usage in plantations, and the average *annual* rates of application are low, *per application* the amounts and types of fertilizers are broadly similar to those in agriculture (Table 1). There is far less frequent use of fertilizers in forest plantations, where applications during the first year are common but later applications range from annually to never. The forms of fertilizer used in forestry mirror those used in agriculture, but some forestry-specific blends are available.

Like other cropping systems, the emphasis of most forest fertilization research has been on diagnosis of nutrient limitations in specific contexts (i.e. combinations of soils, climate, species and management) using soil and plant analyses, and the refinement of fertilizer rate, timing, form and placement options (Fox et al. 2007; Gonçalves and Barros 1999; Smethurst et al. 2004a). Fertilizer placement in a plantation considers uptake efficiency and the relative value of placement options. Planting densities are commonly 1000-2000 trees per ha, which means plants are several meters apart. Young tree seedlings have only small root systems. Therefore, applications around planting time are usually localized in concentrated spots or bands 10-50 cm from the planting position on or below the soil surface, or over small areas close to the plant (Smethurst and Wang 1998). As the root system develops, the zone of application usually increases in area until totally broadcasting the fertilizer becomes efficient (Attiwill and Adams 1996; Smethurst et al. 2004a), which in most countries is the cheapest and preferred way to apply fertilizer. Modern navigational methods aid the selection and recording of ground or flight paths for fertilizer application, which in-turn improves the uniformity of application, and improves the ability of pilots to avoid buffers and other areas that are not to be fertilized (e.g. McBroom et al. 2008).

Examples of Forest Fertilization

Slow-grown conifers Some plantation conifers in Europe are grown in rotations of several decades (e.g. 92 years in central Sweden) and fertilized at planting with multi-nutrient mixes (Evers 1991). Thereafter N fertilizers are applied at various intensities up to 150 kg N ha^{-1} every 5 years, but more commonly less frequently or never (Eriksson et al. 2007). When these plantations are fertilized, it is commonly by broadcasting calcium ammonium nitrate or NPK mixtures.

Medium-growth-rate conifers Coniferous plantations in Australia and the south-eastern USA grown in 15- to 30-year rotations are commonly fertilized at establishment with NPK mixtures applied close to the planting position, and

Table 1 Summary of fertilizer use in selected plantation forest and agricultural systems.

Crop, Country	Nitrogen			Phosphorus			Ages or frequency applied	Other nutrients commonly required
	Average rate applied (kg ha^{-1} $year^{-1}$)	Common high rate (kg ha^{-1} $application^{-1}$)	Common forms*	Average rate applied (kg ha^{-1} $year^{-1}$)	Common high rate (kg ha^{-1} $application^{-1}$)	Common forms[1] (years)		
Forest plantations								
Eucalyptus, Brazil	7	20	U, AS, MAP, DAP	8	53	PR, MAP, DAP	Split 0-2 years	K, B
Pinus, USA	6	224	U, DAP	2	50	DAP, SP, PR	0, 2-22 years	B, K, Mg
Pinus, Australia	4	208	U, AS	2	112	DAP	0, 1-25 years	K, S, Cu, Zn, B
Eucalyptus, Australia	10	104	AS, U	4	54	DAP	0, 1-12 years	K, S, Cu, Zn
Agricultural systems, Australia								
Dairy	20	200	U	25	75	MAP, DAP, SP	1-4/year	K
Sugarcane	160	300	U	20	38	SP, DAP	1-2/year	K
Horticulture	100-800	8-64	U, DAP, MAP, KN	18-100	2-10	DAP, MAP	1-12/year or	K fertigation every 1-2 days
Cereals, oilseeds	30	200	U, AS	10	10	SP	1/year	K, S

Main sources: Barros and Novais (1996) Barros et al. (2004), Gonçalves et al. (2008), Albaugh et al. (2007), May et al. (2009b)

* U urea, AS ammonoium sulphate, MAP, mono-ammonium phosphate, DAP di-ammonium phosphate, PR phosphate rock, SP superphosphate including triple superphosphate, KN potassium nitrate

application rates are 10-50 kg ha^{-1} each of N and P (Fox et al. 2007; May et al. 2009b). Established stands receive nutrients at high rates of 208-324 kg N and 50-112 kg P ha^{-1} broadcast every 5-15 years.

High-growth-rate eucalypts Some eucalypt plantations in Brazil are grown on 6-year rotations that receive 2-3 applications of 20 kg N and 53 kg P ha^{-1} (mainly as monoammonium phosphate and diammonium phosphate) during the first 2 years, plus K and B (Barros et al. 2004; Gonçalves et al. 2008). Eucalypt rotations of about twice the length are used in Australia, with generally higher N and lower P rates than those in Brazil.

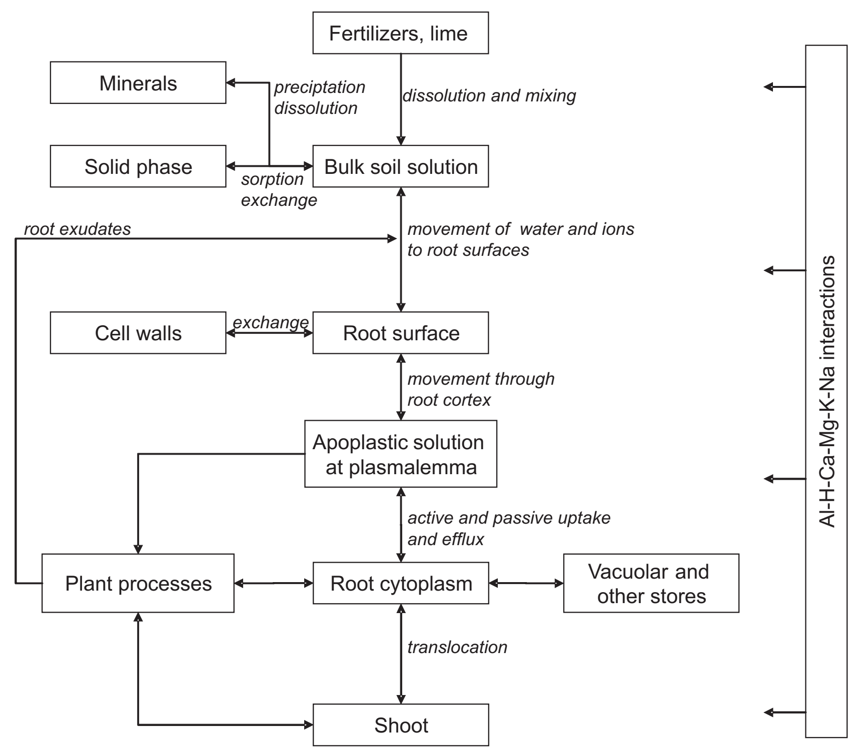
Liming

The use of lime (including dolomite) has increased in forestry during the past few decades in response to a perception that soil acidification and concomitant nutrient deficiencies threaten forest ecosystems. Liming of forests occurs predominantly in Central and Northern Europe (Kreutzer 1995; Meiwes et al. 2002). In Europe, soil acidification has accompanied the atmospheric deposition of nitrogen and sulphur generated from coal-fired power stations and from automobiles, i.e. the 'acid rain' effect. The realization of its potential consequences for forestry developed in the 1970s and 1980s, with the expectation that as a predisposing stress it would contribute to an increased incidence of toxicities and nutrient imbalances that would slow forest growth or in some cases lead to mortality (Hüttermann 1985; Matzner and Ulrich 1985). The accompanying critical load concept (Sverdrup and de Vries 1994) influenced many forest managers in Europe to commence or increase the use of lime (including dolomite). However, data on forest growth later indicated faster rather than slower growth of forests (Binkley and Högberg 1997), suggesting that the beneficial N- and S-fertilizer effects of atmospheric depositions outweighed any negative effects of acidification for several decades at least.

Liming can also have negative consequences associated with humus decay, nitrate concentrations in seepage water, mobilization of heavy metals, shallower root systems, boron deficiency and pathogens (Kreutzer 1995). Further, liming has had little effect on acidity in soil per se, because it is applied to established forests with a litter layer, and most of the chemical changes occur only in the litter layer. Changes in litter chemistry can result in higher rates of nitrification and increased rates of nitrate leaching at a catchment scale, and other adverse outcomes (Löfgren et al. 2009). Far more important to countering the effects of acid deposition than liming are the trends in electricity production during the past few decades that have reduced S deposition by 90% and N deposition by 50% in southern Sweden, for example (Löfgren et al. 2009).

Liming is also used routinely by some plantation forestry companies in Brazil to counter soil acidity, but its main purpose is to correct Ca and Mg deficiencies. This practice is not universal amongst plantation companies in that country, and experimental results indicate that liming to correct acidity is not warranted when planting with *Eucalyptus* or *Pinus* species, which are tolerant of acid soils (Gonçalves et al. 1997). What appears to be an unnecessary use of lime in Europe, and in some cases in Brazil, underscores the risks associated with acting on expected soil chemistry and plant growth effects without confirmation of the latter under normal field conditions. While some progress has been made in our understanding of the effects of forest liming, we particularly need to separate the effects of liming to alleviate the toxic effects of H and Al from those on nutrient availability at root membrane to stand scales. There is a larger knowledge base for some agricultural species, but in that domain too we still lack an adequate quantitative, mechanistic, understanding of the interactive effects of liming across a range of spatial and temporal scales. A schematic of the main pools and processes involved is presented in Fig. 1. A number of these aspects have been studied in

Fig. 1 Schematic diagram of the main soil-plant processes involved in Al-H-base cation availability responses to liming and fertilization.



detail for some soil-plant systems, but quantitative links have not been established for any plant-soil system. Until such understanding and quantification is available, we will have to rely on calibrated, empirical relations between fertilizer or lime applications and ecosystem responses.

Fertilizer use in agriculture

There is a very wide range of fertilizer practices used in agriculture due to the variety of natural and socio-economic conditions, crop requirements, nutrient forms and fertilizer availability. Examples are provided in Table 1 for some Australian agricultural systems, which show that relatively high annual rates are used in horticulture and sugarcane, and lower rates in cereals, oilseeds and dairy systems. These latter systems have rates about twice those in intensively managed forest plantations. Annual rates of fertilizer usage in Australian agriculture are within the large range reported for cropping and pastures in the UK (Chalmers 2001), vegetable crops in China (Chen et al. 2004), and also broad-acre and horticultural crops in various regions of the world (Crews and Peoples 2005).

Understanding Forest Nutrition and Growth

Nutrient cycling

Although fertilizer management in forest plantations is similar in principle and practice to many agricultural situations, differences in some aspects of nutrient cycling need to be considered. Prior to 1960, plant nutrition as a discipline had no particular emphasis on forests, but in the period 1960-1990 forest nutrition developed as a discipline of research by focusing on nutrient budgets and nutrient cycling in a variety of natural and managed forest systems (Smethurst 2004). Some of these systems had been fertilized, but not all. Comerford (2002) lists 16 key texts on forest soils published between 1983 and 2000 that document an increasing emphasis on nutritional management. To these can be added Bowen and Nambiar (1984), Nambiar and Brown (1997), and Gonçalves (2004) that specifically develop the topic in a plantation context.

As Comerford (2002) highlighted, there are several aspects of forest soils that are distinct from agricultural systems: time between harvests, nutrient cycling, erosion, topography, fertilization practices, irrigation, soil temperature, utilized soil depth, stoniness, remoteness from markets, and surface soil organic horizons. All of these differences impinge to some degree on fertilizer management, some of which are further explored here.

In trees, the annual requirement for nutrients for new growth is partially met by drawing on internal pools in older tissues rather than meeting nutrient demand entirely by uptake from soil. In this context, internal cycling includes the

withdrawal of nutrients from aging or dying tissues and retranslocation of those nutrients to younger tissues. The importance of this process had been recognized by the 1970s (Wells and Jorgensen 1975), and it has been quantified in a number of forest systems since. In a 13-year-old, N-deficient *Pinus radiata* plantation, N fertilization led to a 45% increase in wood production and 350% increase in N retranslocation, showing increased reliance on retranslocation as growth rate increased (Fife and Nambiar 1997). Internal cycling of nutrients in three *Eucalyptus species, Acacia mearnsii* and *Pinus radiata* was studied between 12 and 22 months of age, during which 31-60% of N present in young, green foliage, 54-63% of P and 18-38% of K was retranslocated (Fife et al. 2008). Hence, such dependence on retranslocation probably exists among all or many forest plantation species. In contrast, annual agricultural crops depend almost entirely on uptake, during which sub-annual transfers of carbohydrates and nutrients are important for grain, fruit or tuber production.

Cycling of nutrients external to the plant is also prevalent in forests that have commenced above- or below-ground litter production, and it can account for a significant component of annual nutrient availability to tree roots. For example, tropical plantations of various species accumulate in litter 80-660 kg N and 4-20 kg P ha^{-1}, which is more than in many natural tropical forests (O'Connell and Sankaran 1997) and generally more than the average annual amounts of N and P accumulated in trees of tropical forest plantations (Gonçalves et al. 1997). Hence, retention of this material and harvesting residues between rotations is essential to reduce or alleviate the need for fertilizers during the early phase of the next crop (Nambiar 2008). Conversely, slow decomposition of litter in some systems, particularly in cold climates, immobilizes large pools of N and other nutrients (Tamm 1995). This build-up of nutrients in litter layers limits nutrient losses via leaching from these ecosystems, but it can also contribute to N deficiency in trees.

Links between nutrient cycling and catchment-scale outcomes were made early in forestry because some aspects of forestry practices were controversial, i.e. clearfelling and complete vegetation control using herbicides could lead to high nitrate concentrations in streams and ground water (Vitousek and Melillo 1979). Later studies have shown that N and P fertilizer in forestry leads to generally small and transient increases in N and P concentrations in stream water (Binkley et al. 1999). More recently, practices in agriculture have come under scrutiny in a nutrient context for potential adverse catchment scale and greenhouse gas outcomes (McDowell 2008). Agriculture generally, via fertilizer use, has caused a much larger perturbation of global nutrient cycles than forestry (May et al. 2009b). For example, by about 1990, global N fertilizer production, which is mainly used to produce food, and other anthropogenic influences had doubled the rate of N transfer from atmospheric to terrestrial pools compared to that which would otherwise have occurred due to natural processes (Vitousek et al. 1997). This proportion has probably increased substantially during the past decade.

Nutrient flux density and uptake kinetics

Developing a mechanistic understanding of nutrient uptake processes has led to the realization that nutrient uptake at the cell membrane level of roots and mycorrhizal hyphae was an active process mediated by enzymes. Together with nutrient supply phenomena in soils, supply and uptake could be mathematically modeled (Barber 1995; Tinker and Nye 2000). Between 1970 and 1991, the need to experimentally control plant growth rates and nutrient concentrations led to the development of hydroponic culture techniques that supplied all nutrients at non-limiting concentrations, except for one limiting nutrient (Asher and Blamey 1987; Asher and Cowie 1970; Ingestad 1971). Supply of the limiting nutrient (usually N) conformed to a schedule that directly led to control of the growth rate of the plant. Different exponential growth rates resulted in different but stable internal nutrient concentrations, which greatly assisted in the testing of various hypotheses of nutrient-growth relations in plants (Ericsson et al. 1995; Ingestad 1982).

However, Ingestad came to the conclusion that concentrations of nutrients in hydroponic and soil solutions and uptake kinetics of plant roots were unimportant for controlling plant growth rates (Ingestad 1982). Instead, the rate of nutrient replenishment was critical, which he and his coauthors termed the nutrient flux density approach. This method was also applied to several field experiments in forests around the world (Albaugh et al. 2007; Linder 1995) and was adopted by scientists working on nutrient-growth relations of other forestry, agricultural, and aquatic species (e.g. Groot et al. 2002; Hawkins et al. 2005; Macduff et al. 1993; Pintro et al. 2004; Raven 2001), because of the high level of control it offers over plant growth rates and internal nutrient concentrations.

The nutrient flux density approach presented a dilemma for some scientists working in the more common paradigm where concentrations in growth solutions and uptake kinetics were important (Macduff et al. 1993; Raven 2001). Sands and Smethurst (1995) subsequently demonstrated that these two approaches were not necessarily inconsistent by using uptake kinetic principles to model nutrient uptake and plant growth reported for one of Ingestad's experiments. A solution concentration of 50 mM inorganic N was required (via periodic or continuous replenishment) to produce a relative growth rate of 0.25. Building on the earlier work of Tinker and Nye (2000) and Barber (1995), nutrient supply and uptake theory has since been used to simulate nutrient uptake and growth of a eucalyptus plantation over several years with simultaneous potential limitations of N, P, light, water or temperature (Smethurst et al. 2004b).

CEC and base cations

Forest soils are generally more acidic and organic than soils used for agriculture. Experience with forest soils has questioned traditional views developed primarily

in an agricultural context that use cation exchange capacity, base cation saturation and exchangeable cation concentrations as indicators of base cation availability (Ross et al. 2008). In such forest soils, the source of charge is mainly organic matter, and cation retention cannot be explained by simple exchange phenomena. Ross et al. (2008) argue four salient points that apply to acid soils across agriculture and forestry: (1) new measures of exchangeable Al and H are needed, (2) base saturation should be abandoned as a measure of base cation availability, (3) the paradigm that higher pH accompanies higher CEC does not hold, and (4) CEC should not be used to indirectly infer base cation availability. These observations will become more pertinent as agricultural and forestry soils acidify, which is a long-term trend globally, and as society is forced to use more acid soils to grow food and fibre.

In many parts of the world, salinity or sodicity adversely affects crop growth, and the problem is expanding. During recent decades, Na has been recognized as a functional nutrient for many agricultural plant species, and to some extent it can substitute for the functions of Ca, Mg and K (Subbarao et al. 2003). One implication is that increasing Na availability and uptake can reduce the need for these other base cations, and lower critical foliar concentrations can be used as a guide to fertilizer needs. However, few studies have demonstrated Na substitution of other bases under field conditions. A recent demonstration of this effect in a plantation forestry context comes from Brazil, where K depletion after several decades of eucalypt cropping led to substantial K deficiency (Almeida et al. 2009). Trees responded substantially to K fertilizer applications, and about 40% of that response was also achieved by Na fertilization alone.

Productivity modeling that includes nutrients

Agricultural crop productivity modeling that accounts for species-specific responses to light, water, temperature, and nitrogen was already well developed more than a decade ago (Hanks and Ritchie 1991; Keating et al. 2003), and has since expanded in sophistication and application. A similar model has been developed for forest plantations (Landsberg and Waring 1997), but it considers nutrients by using only a generic fertility factor, and it cannot account for fertilizer applications. A more mechanistic model has been developed that considers some silvicultural operations used in plantation forestry, including N fertilization (Battaglia et al. 2004), which was used to simulate N and P uptake and estimate growth limitation due to light, water, N and P (Smethurst et al. 2004b). Other forest productivity models have been developed that account for one or more nutrients (usually N), but none combine a high level of silvicultural flexibility with detailed nutrient dynamics and uptake by trees and weeds (Smethurst 2007). These process-based plantation forestry models also do not yet have the sophistication to account for all the options available for managing fertilizers, e.g. fertilizer forms and placement, but such developments are possible. Such detailed fertilizer management options can instead be compared using more empirical models or decision support systems based on experience and financial information (Fox et al. 2007; May et al. 2009a).

Nutrient use efficiency

Forest researchers have had an interest in nutrient use efficiency (NUE) for several decades. Based on litterfall as a surrogate for growth and net primary productivity (NPP), and litter N content as a surrogate for N supply, it was asserted that the more nutrient that was used the less was its NUE, i.e. biomass produced per unit of resource supply decreased with an increase in supply (Vitousek 1982). With actual measures of above-ground NPP (ANPP), Binkley et al. (2004) sought evidence that this was the case for the resources of light, water and nitrogen, and found that the few data available supported the opposite hypothesis, i.e. resource use efficiency increased with increasing resource capture. For example, across 14 *Eucalyptus* stands in Brazil, Stape et al. (2004) found that ANPP per unit of N uptake, increased about 30% with a 200% increase in N uptake, while litterfall per unit of N uptake and litterfall proportion of ANPP both decreased by about 50%, with a 300% increase in ANPP.

A key concept in agriculture is that resource use efficiency is based on product yield per unit of resource supply (e.g. Passioura 2004 for water). But for nutrients, the contribution of both fertilizer and soil sources needs to be considered, and resource capture needs to be separated from resource use within the plant. There are few data in agriculture or forestry that allow a full analysis of nutrient use efficiency, but instead product yield can be expressed per unit of external resource input (e.g. irrigation or fertilizer). This latter index has also been referred to as the partial factor productivity (PFP) of an applied nutrient (Dobermann 2007). Nutrient use efficiency can also be expressed as biomass or product yield per unit of nutrient taken up regardless of the nutrient source, which approximates to the inverse of the average concentration of a nutrient in a plant. It is important that such concepts are more fully understood by including below-ground productivity and measures of resource supply and resource capture, and that the implications for fertilizer practices are clarified.

Various fuel sources are used or considered for biofuel production, but these can have a very wide range of PFP values (Table 2). These data indicate that corn, cereals and pasture have very low PFP values (0.6-144) compared to some eucalypt plantations that had a low requirement for N fertilizer (2-14 kg), but similar to pine plantations that had a high N fertilizer requirement. Biofuel production requiring little or no fertilizer input would have a PFP value approaching infinity, e.g. in riparian plantings of trees and grasses that utilize nutrients in wastewater or polluted groundwater (Gopalakrishnan et al. 2009) or in

Table 2 Comparison of fertilizer nitrogen use efficiencies (NUE; PFP as defined by Dobermann 2007) of typical biomass produced from cereals, corn, and perennial pasture compared to stem wood from plantations that had relatively low (eucalypt) or high (pine) N fertilizer requirements. Corn and cereal biomasses were calculated using a harvest index (grain biomass to total biomass ratio) of 0.5 and 0.25 respectively (Donald and Hamblin 1976).

Crop	Fertilizer NUE (kg yield per kg N fertilizer)		Reference
	Minimum	Maximum	
Corn	1.2	2.6	Dobermann et al. 2002
Cereals	124	488	Dobermann 2007
Perennial pastures	32	144	Brouder et al. 2009
Pine plantations	16	44	Albaugh et al. 2004
Eucalypt plantations	2,222	13,545	Stape et al. 2004

parts of Europe and North America with high atmospheric deposition. As biofuel technologies develop to better cope with woody materials, it is expected that more of this feedstock will be used and thereby increase the N-use efficiency of biofuel production (Galloway et al. 2008), but it will be important to consider the N fertilizer requirement of the particular plantation system under consideration.

Production systems with less fertilizer

There is a concern that the availability of inorganic N and P fertilizers will diminish as the surplus of supply over demand decreases (FAO 2008, Huang 2009) and as mineral reserves of P-containing rocks are depleted (Cordell et al. 2009). However, others argue that world reserves and resources for N and P appear adequate for at least the next two years (FAO 2008) and the foreseeable future (Fixen 2009). Under both scenarios, the price of fertilizers could increase relative to the cost of other farm inputs. Lack of availability, or economic pressures could therefore reduce the per ha use of these fertilizers and necessitate food and fibre production using lower nutrient input systems. This trend could in-turn expanded interest in the use of rhizosphere and mixed-species technologies that potentially add N and better utilise existing sources of soil N and P otherwise unavailable to crop plants. These technologies include enhanced P uptake by roots and mycorrhizae via organic acid and phosphatase production (Jones 1998, Richardson et al. 2009), symbiotic (Forrester et al. 2006) and non-symbiotic biological N-fixation, and improved plant root nutrient uptake kinetics (Bassirirad 2000, Raghothama 1999). There is scope for (1) using existing genotypes that can up-regulate these mechanisms, (2) selecting and breeding for new genotypes of plants and microbes, and (3) genetic engineering to induce or enhance these processes in important crop species (Schachtman and Shin 2007, Richardson et al. 2009). There will probably be a greater need for these developments in agriculture than in forestry, so important opportunities might develop for plantation forestry by being aware of such trends in agriculture. However, studies of forest and other non-agricultural crop species have contributed significantly to our current understanding of these processes, because of their importance in low-fertility, non-agricultural systems.

Mycorrhizae, fungal symbionts that infect the root system, act as a very fine extension of the root system with a high surface area to biomass ratio that enhances under some conditions nutrient and water uptake and the ability of a plant to cope with biotic and abiotic stresses. In return for these potential benefits, the plant supplies carbon to the fungus for growth and metabolism. Many of these functions are genetically mediated (Graham and Miller 2005). In relation to nutrient uptake, plants benefit most from the mycorrhizal symbiosis in terms of biomass growth and survival under conditions of low availability of poorly-mobile nutrients, e.g. P in highly P-limited natural and man-made ecosystems (Chen et al. 2008). In contrast, under high nutrient availability, infection and growth of mycorrhizae can be negligible, or the cost in terms of carbon can reduce plant growth where nutrient uptake is not enhanced by mycorrhizae. These principles have been amply demonstrated in controlled environment and field conditions using a variety of plant species (e.g. perennial versus annual, woody versus non-woody, domesticated versus non-domesticated species) (Graham and Miller 2005). However, field studies can be difficult due in-part to a limited ability to control and measure the level of infection by inoculated and endemic species of fungi. Organic acid and phosphatase enzyme exudates increase the availability of inorganic and organic soil P, respectively, by converting solid-phase P to liquid-phase phosphate, which is the main form of P taken up by roots and mycorrhizal hyphae of crops (Richardson et al. 2009).

Nitrogen-fixing plants have been of interest in plantation forestry for many years as primary crop species or as nurse/companion crops to other main species in plantation forests or agro-forestry systems (Forrester et al. 2006). Increased N availability benefits in such systems have been well-demonstrated (Binkley and Giardina 1997), but major deterrents to their adoption on a large scale have been management complexity and economic viability. An overall financial benefit is not obvious unless fertilizer costs are very high or the wood value gained is very high (Turvey and Smethurst 1983). These financial benefits will probably become more obvious if fertilizer and fibre shortages develop. If or when that situation eventuates, plantation forestry and agriculture will need to seriously consider mixed-species systems, for which there are many generic and system-specific research and management questions remaining to be answered.

Ion Flux and Membrane Transporter Technologies

In recent years, the use of ion flux and membrane transporter technologies have started to expand our understanding of the nutritional physiology of trees. Wood formation has a particular dependence on potassium (K), the supply of which to cambial cells is regulated by K^+ channels (Langer et al. 2002). In *Populus tremula,* one transporter was continuously present at a low level, suggesting a house-keeper function, but the levels of two others followed the annual variation in plant growth (Langer et al. 2002). Functioning of theses transporters (and hence uptake of K into cambial and expanding xylem cells) depends on the necessary H^+-gradient being generated by a H^+-ATPase in the plasma membrane, and this response can be initiated within a few hours of the addition of auxin to dormant twigs (Arend et al. 2002). Similar transporter and ion flux studies in tree roots also indicate a key role for H^+-pumping to maintain the electrochemical gradient that drives the fluxes of K and Na (Knowles 2007; Sun et al. 2009). However, when measuring fluxes of these cations, care needs to be exercised in the use of the non-invasive, ion-selective flux microelectrode technology, because one needs to correctly account for the non-ideal, ion-selective behavior of the resins used to make the microelectrodes (Knowles and Shabala 2004).

Using *Populus, Eucalyptus,* and agricultural species (Escalante-Perez et al. 2009; Knowles 2007; Sun et al. 2009), these technologies are now elucidating the genetic and physiological basis to salt sensitivity and tolerance. Regulation of the proton gradient across the plasma membrane reduces Na^+ influx via non-specific cation channels and simultaneously reduces K^+ efflux through depolarization-activated channels. The addition of Ca^{2+} markedly enhances these processes and thereby assists in maintaining K^+/Na^+ homeostasis.

Ion-flux technologies are also available for nitrogen, but not yet for phosphorus. Simultaneous measurements of ammonium, nitrate and proton fluxes around roots of *Eucalyptus nitens* revealed a preference for ammonium, spatial and temporal variations in fluxes in the 20-60 mm region from the root tip, no affect of proximity to root hairs or root laterals, and Michaelis-Menten-style uptake kinetics (Garnett et al. 2001, 2003). Ammonium preference is a more common observation in forest ecosystems than in agricultural systems (Kronzucker et al. 1997; Min et al. 2000). Such results encourage the continued use of ammonium-based fertilizers in forestry. Increased development and use of ion-flux technologies will be needed as we seek to further expand our understanding of plant nutritional physiology and improve fertilizer management, but we need to be cognizant of some current limitations. For example, these methods are mainly suitable for young plants in controlled environments that experience very different growing conditions to field-grown plants, and the lower limits of concentration detection are not as low as the concentrations at which uptake occurs in many forestry and agricultural cropping systems.

Indicators of plantation response to fertilization

There is a well-established method of calibrating soil and plant indicators of potential growth (or yield) response to fertilization (McLaughlin et al. 1999; Smith and Loneragan 1997). This method requires that many fertilizer experiments be established in time and space to capture climatic and landscape variability. Yield of the unfertilized treatment is expressed relative to maximum growth with fertilizer, and these data plotted as a function of the indicator, e.g. a soil or leaf analysis. The value of the indicator at the point where relative yield decreases significantly from below 1.0 (generally taken as 0.90 or 0.95 relative yield) is referred to as the critical value for that indicator. Instead of relative yield, other yield response criteria can also be used, e.g. percent increase in growth due to fertilization.

Fertilizer needs in agriculture commonly take into account soil and plant analyses that are well calibrated. As plantation forestry intensifies and the relative cost of fertilizer increases there will be a need to further develop and apply suitable soil and plant analyses. Appropriate calibrations and their use will not only guide fertilizer use in low- to medium-input systems, but they can also be useful for avoiding the over-use of fertilizers and concomitant environmental problems such as those that occur already in parts of Europe, USA, China and Mexico (Vitousek et al. 2009). Fertilizer practices in forestry should be developed while avoiding over-use.

This protocol for calibrating potential indicators of nutrient deficiency is rarely fully applied in forestry, because resources have often not been available to cater for the long crop cycles and large plot and plant sizes. Some examples are available, and critical indicator values are also inferred, but less-reliably so, from growth and nutrient indicator surveys across operational plantations. Such inferences have also been developed from growth and nutrient relations within just one or a few fertilizer experiments. In the following paragraphs, examples of nutrient limitations in several major plantation regions of the world are described along with the criteria used to predict fertilizer responses.

Pinus plantations, south-eastern USA

A large concentration of forest plantations of *Pinus elliottii* and *P. taeda* (13 M ha) are grown in their native range in the south-eastern USA, and fertilization has been a key component of management intensification during the past five decades (Fox et al. 2007). Nutritionally, these plantations are severely limited by low P and N supply if unfertilized. P-fertilizer is needed at planting (Pritchett et al. 1961), and thereafter a combination of N and P is far better than either nutrient alone (Amateis

et al. 2000). The concentration of P in an acid extract (Bray2-P) best discriminated between responsive and non-responsive sites at planting (Ballard and Pritchett 1975). Once established, leaf area index (LAI) is the main diagnostic. A fully stocked stand with stem cross-sectional areas at 1.3 m height greater than 22.9 m^2 ha^{-1} should have an LAI of at least 3.5, unless there are other obvious problems that have altered LAI, e.g. fire, ice, insects etc. (Fox et al. 2007). It is possible to use these criteria, because water is generally less limiting than low N and P supply at this stage of the crop.

Pinus and *Eucalyptus* plantations, Australia

Almost 2 M ha of *Pinus* and *Eucalyptus* plantations are grown in Australia. Where grown on ex-native forest sites that do not have a history of P-fertilization for agricultural production, applications of P fertilizer at planting are essential (Boomsma 1949). Various indices of soil, plant and litter P have been sought for these plantations (May et al. 2009b). Although a common basis for assessment is still lacking, some of these indexes have been calibrated for specific soil-climate-species-management contexts, e.g. $CaCl_2$-extractable P for *Eucalyptus globulus* and *E. nitens* in temperate Australia (Mendham et al. 2002) and total P concentration in litter for *Pinus radiata* in south-east South Australia (May et al. 2009a).

As for *Pinus* plantations in the south-eastern USA, LAI has been recognized as a key determinant of potential growth response to N fertilization in *Pinus radiata* plantations in south-east South Australia (May et al. 2009a) and in *Eucalyptus nitens* plantations in Tasmania (Smethurst et al. 2003). Soil and litter N analyses have also been examined as indicators for these plantations; litter N concentrations in *Pinus radiata* were significantly correlated with response to N-plus-P fertilization (May et al. 2009a). The critical concentration of total N in surface soil was 6 mg g^{-1} for *Eucalyptus nitens* plantations in Tasmania (Smethurst et al. 2004a) and 2 mg g^{-1} for *E. globulus* plantations in Western Australia (White et al. 2009), which illustrates the contextualization required for many critical concentrations based on soil analyses.

Deficiencies of K in *Pinus radiata* occur under some circumstances in Australia, e.g. on ex-farmland where decades of K removals in agricultural products have not been replaced by fertilization (Smethurst et al. 2007). Although foliar analysis appears useful as a diagnostic tool in these circumstances, further refinement of the critical concentrations is warranted to account for soil type, management and climate (Smethurst et al. 2007).

Eucalyptus and *Pinus* plantations, Brazil

The area of eucalypt and pine plantations in Brazil has increased rapidly during the past two decades, and now totals 4 Mha for eucalypts and 2 Mha for pines. Applications of P and K were recognized early as necessary in many regions (Barros et al. 2004). Little or no N fertilization was needed for the first rotation. The incidence and severity of N deficiency on these sites is expected to increase with subsequent rotations, and relative growth of 0.74 to 0.98 has recently been documented in later rotations by age 2 years at 11 sites in São Paulo State (Pulito 2009). At three of these sites, trees had already reached or were close to harvest age of 7 years, and in each of these cases relative growth had increased from 0.74-0.83 at 2 years of age to 1.0 at around 7 years, indicating that the earlier response to N fertilizer had disappeared. The reason for this change was not investigated, and raises the hypothesis that N or another resource became limiting between 2 and 7 years. Specific for either Eucalyptus or Pinus, critical concentrations of organic matter had earlier been proposed as an indicator of the need for N fertilization (Barros et al. 2004), but this criterion was not supported by the Pulito (2009) data. Resin-P for P fertilization, and exchangeable K for K fertilization are still a current recommendation and critical concentrations of these indicators depend on clay content. (Barros et al. 2004).

Soil solutions as indicators of nutrient supply

In agriculture and forestry, the development of soil and foliar analyses as indicators of nutrient deficiency has largely been the responsibility of public organizations like universities and state or national departments of research and extension. However, during the past decade it has become difficult for these organizations to resource this activity, and in many cases it has been dropped as an important objective unless the user-pay principle is applied. Meanwhile, crop genotypes, climate, crop management, and soil conditions have changed. Such changes would be expected to in-turn change the critical concentrations of soil and foliar diagnostics. With food and fibre shortages increasing globally, and system inputs becoming more expensive, including fertilizers, there is a mismatch between the need to use resources more efficiently, and the knowledge base for making fertilizer management decisions. Either traditional systems for developing critical nutrient concentrations need to be re-built, or new technologies need to be developed that are less expensive. This dilemma developed in plantation forestry some years ago and led to consideration of nutrient concentrations in soil solutions as potential indictors that were more generic than traditional, soil-type-specific measures, which rely on strong acid, alkaline or salt extracts (Smethurst 2000).

The desire to interpret nutrient availability from nutrient concentrations in soil solution also motivated others to seek appropriate methods. For example, Barraclough (1989) demonstrated how critical soil solution concentrations for agricultural crops in the UK might be used to derive more accurate critical

concentrations of more traditional soil indices by accounting for volumetric soil water content (θ_v). A soil of $\theta_v = 0.34$ was estimated to have a critical Olsen P value of 7 mg g^{-1}, in comparison to a drier soil ($\theta_v = 0.30$) requiring a higher critical Olsen P value of 23 mg g^{-1}. This motivation and operational simplicity were also behind development of a dilute calcium chloride extract (0.01 M $CaCl_2$) as an indicator of nutrient availability in European agricultural soils; this solution mimics the ionic strength and pH of soil solutions (Houba et al. 2000). Such an extract was particularly useful for identifying P deficiency in pastures (Dear et al. 1992) and temperate eucalypt plantations (Mendham et al. 2002).

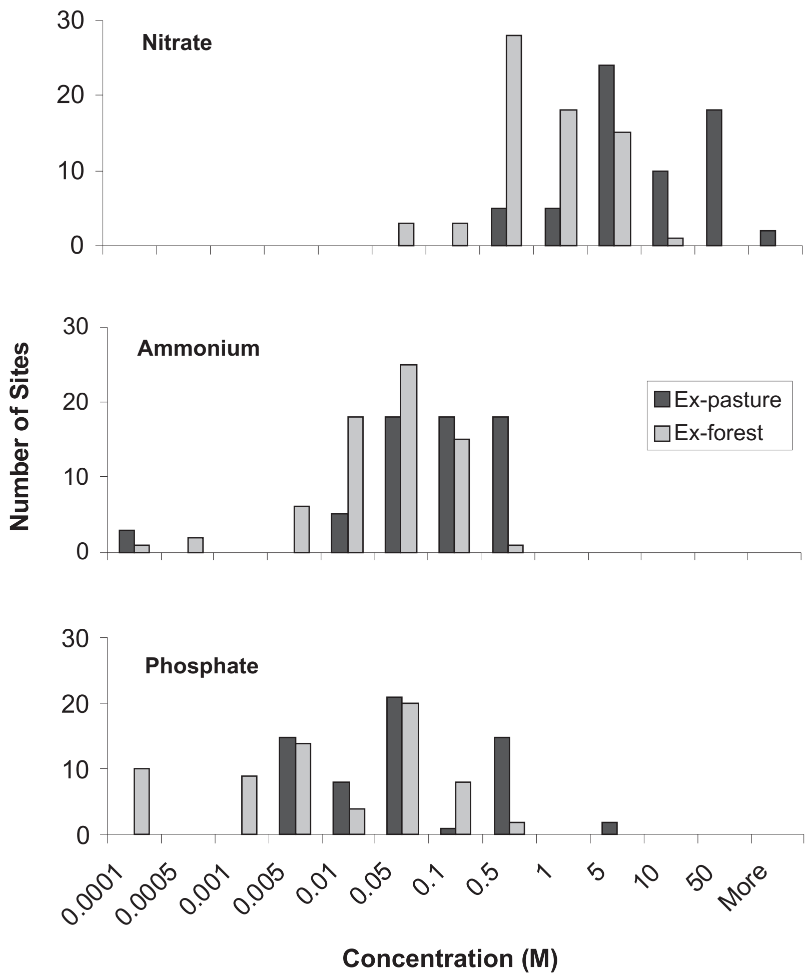
In a research context, soil solution technology has proven more useful than traditional measures of soil fertility where well-established calibrations are lacking (e.g. Smethurst et al. 2001; 2007). Can this technology be developed also as an operational method? The principle of using soil solutions for inferring nutrient deficiencies relies on three main steps. Firstly, the concentration of the inorganic nutrient needs to be measured in a paste extract. Secondly, this concentration may need adjusting for potential dilution effects that can occur during preparation of the paste. The adjusted concentration is an estimate of the concentration in bulk soil solution. Thirdly, the bulk soil solution concentration is interpreted on the basis of that which is required at root surfaces to maintain near-optimum growth.

There is a possibility that the soil solution method could be adapted to low-cost, portable equipment by using simple centrifugation or suction methods to extract the paste solution and by analyzing the solution using portable water analysis equipment (Osborne et al. 2001). The essential aspects of this method were demonstrated in a survey of forest plantations in four regions of Australia, where a large part of the variation in soil fertility is attributed to fertilizer history, in particular whether there had been a pasture phase accompanied by fertilizer inputs. Paste samples were prepared using de-ionized water, and solution was extracted using porous ceramic tips (Rhizon© solution samplers purchased from Eijkelkamp) to which a partial vacuum had been applied. Solutions were analyzed for NH_4, NO_3, PO_4 and K on a portable spectrophotometer designed for water analysis (Spectroquant Nova 60 Photometer© purchased from Merck). Due to buffering by the solid phase, concentrations of NH_4, PO_4 and K in soil solution were assumed to be altered little by the addition of water during preparation of the paste, but NO_3 concentrations were adjusted to account for the dilution effect.

Frequency distributions of concentrations of NH_4, NO_3, and PO_4 indicated that higher values were more common on ex-pasture sites than on ex-forest sites (Fig. 2). In a separate study, soil solution NH_4 and NO_3 correctly discriminated between 6 responsive and 2 non-responsive *E. nitens* plantations when fertilized with N.

This level of discrimination was better than that achieved by the commonly used KCl extract (Smethurst et al. 2004a). Soil solution P and its surrogate $CaCl_2$-P were also good discriminators of P responsive sites (Mendham et al. 2002). Even if the soil solution approach is adopted, it will not eliminate the need for field

Fig. 2 Frequency distribution of surface soil NO_3 (top), NH_4 (middle) and PO_4 (bottom) concentrations measured in Australian forest plantations grown on ex-pasture and ex-forest sites. Concentrations were measured using a low-cost, portable nutrient anlaysis system (Osborne et al. 2001).



experiments; instead, its potential to reduce the need for field experiments and to provide a more generic approach to soil fertility assessment warrants further testing.

Conclusions and Knowledge Gaps

This review places several aspects of forest fertilization developments in an agricultural context, and identifies knowledge gaps:

1. Fertilizer use in intensive plantation forestry does not approach the usage seen in the most intensive pasture (dairy) or annual cropping systems on a per ha per year basis.
2. However, intensive plantation forestry systems are similar to some biennial or perennial agricultural systems in the length of the crop cycle and the rates of fertilizer applied per application.
3. Less intensive plantations systems have much longer rotations than in agriculture and much lower rates of fertilizer use, and plantation forestry overall occupies a small portion of the landscape compared with agriculture.
4. Fertilization strategies in forestry consider internal and external nutrient cycling and deep rooting.
5. As an option for improving nutrient use efficiency, both forestry and agriculture will need to further develop rhizosphere and mixed-species technologies.
6. Forest scientists have contributed significantly to developing methods of plant culture that maintain stable internal nutrient concentrations. As a research tool, this development should continue to improve our understanding of nutrient-growth relationships.
7. The development of plant production models that include the mechanistic simulation of nutrient supply, uptake and weed competition are at a similar early stage of development in both agriculture and forestry. Nitrogen modeling is more advanced than other nutrients.
8. Plantation forestry lacks a mechanistic basis for evaluating base cation availability that accounts for Al-pH-root interactions, which is also the situation in agriculture. Further developments in this field could assist in rationalizing the use of lime.
9. Traditional concepts of nutrient use efficiency in forestry have recently been challenged and need clarifying in the context of fertilizer management for food, fiber and biofuel production.
10. There is an on-going need to develop calibrations of traditional types of soil and foliar analyses, but, in some countries, organizations that have developed these calibrations in the past are finding it difficult to resource further work.
11. Testing soil solution approaches of assessing soil fertility are warranted,

because they offer a more generic and affordable approach that might reduce the need for field experimentation.

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Role of nutrients in human health: New insights

K Bhaskarachary

Abstract The importance of nutrition as a determinant of health status of the population has been well recognized. Nutrition is a dynamic science. Our understanding of functions of known nutrients is still not complete. There is a wealth of new information emerging from research on hither to unexplored roles of nutrients and the definition of nutrient itself is under scanner. Among the bio active phytochemicals, carotenoids other than non vitamin A precursors like lutein and zeaxanthin have shown strong evidence in preventing or delaying the age related muscular degenerative disease and lycopene in prostrate cancer. Curcumin is another phytochemical, which is a remarkable inhibitor of oral cancer and cell growth. Tannins and Phytates which were considered as anti nutritional factors have now been found to help in reducing the risk of cancers and cardiovascular diseases. Consequent to westernization of Indian diets, the intake of salt is on the increase and this is not only risk factor for hypertension and also creating imbalance in the sodium/potassium ratio. Recent study had indicated that increased potassium intake and reduced sodium intake can reduce the risk of hypertension. Dietary intake of Potassium among Indians is one tenth of what is recommended. Until recently, the role of nutrients in preventing chronic diseases was not systematically considered in defining dietary recommendations. Therefore there is urgent need to look in to the recommended dietary allowances for these emerging nutrients for various physiological groups.

Keywords Cancer • cardiovascular diseases • nutrition • phytochemicals • vitamins.

Introduction

Nutrition is a dynamic science. Our understanding of functions of known nutrients is still not complete. There is a wealth of new information emerging from research on hither to unexplored roles of nutrients and the definition of nutrient itself is under scanner. The importance of nutrition as a determinant of health status of the population has been well recognized. Diet can modify the pathophysiological processes of various metabolic disorders and can be an effective preventive strategy for various disease processes most of which are known to involve

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oxidative damage. Both nutrient and non-nutrient components of the diet have been recognized for their anti-oxidant and other potential benefits. New scientific evidence gave support to the concept that nutrients were not only essential to the growth, development, and maintenance of tissues, but were also linked to the expression of genetic information, the effectiveness of the immune system, the prevention of cell damage, and in general, to increased resistance to many chronic diseases and even some infectious diseases. This link to health maintenance and disease prevention resulted in a renewed interest and excitement in nutrition that was now expanded beyond the domain of classical nutritional deficiencies. The realization came about that a diet and its nutritional consequences could have a profound influence on the control and prevention of many chronic conditions such as osteoporosis, cardiovascular disease, high blood pressure, and cancer, as well as play an important role in many oral diseases and pathoses such as dental caries, periodontal disease, salivary gland dysfunction, and soft tissue lesions. The present paper is the documentation of beneficial effects of some of the phyto chemicals and emerging new roles of minerals.

Carotenoids

Plant carotenoids are red, orange, and yellow lipid-soluble pigments found embedded in the membranes of chloroplasts and chromoplasts. Their color is masked by chlorophyll in photosynthetic tissues, but in late stages of plant development these pigments contribute to the bright colors of many flowers and fruits and the carrot root. Carotenoids protect photosynthetic organisms against potentially harmful photo oxidative processes and are essential structural components of the photosynthetic antenna and reaction center complexes (Glen and Scolnik 2009). In plants, some of these compounds are precursors of abscisic acid (ABA), a phytohormone that modulates developmental and stress processes (Koornneef, 1986).

Carotenoids with provitamin A activity are essential components of the human diet, and these are abundantly present in Indian foods (Baskarachary et al. 1995; Bhaskarachary et al. 2008). Early observational studies suggested an inverse relationship between lung cancer risk and beta-carotene intake, often assessed by measuring blood levels of beta-carotene (Peto et al. 1981; Ziegler 1989). Dietary intakes of total carotenoids, lycopene, beta-cryptoxanthin, lutein, and zeaxanthin, but not beta-carotene, were associated with significant reductions in risk of lung cancer in a 14-year study of more than 27,000 Finnish male smokers (Holick et al. 2002), while only dietary intakes of beta-cryptoxanthin and lutein and zeaxanthin were inversely associated with lung cancer risk in a 6-year study of more than 58,000 Dutch men (Voorrips et al. 2000).

The results of several prospective cohort studies suggest that lycopene-rich diets are associated with significant reductions in the risk of prostate cancer,

particularly more aggressive forms (Giovannucci 2000). In a prospective study of more than 47,000 health professionals followed for eight years, those with the highest lycopene intake had a risk of prostate cancer that was 21 percent lower than those with the lowest lycopene intake (Giovannucci et al. 1995). Those with the highest intakes of tomatoes and tomato products (accounting for 82 percent of total lycopene intake) had a risk of prostate cancer that was 35 percent lower and a risk of aggressive prostate cancer that was 53 percent lower than those with the lowest intakes. Similarly, a prospective study of Seventh Day Adventist men found those who reported the highest tomato intakes were at significantly lower risk of prostate cancer (Mills et al. 1989), and a prospective study of U.S. physicians found those with the highest plasma lycopene levels were at significantly lower risk of developing aggressive prostate cancer (Gann et al. 1999). Because they are very soluble in fat and very insoluble in water, carotenoids circulate in lipoproteins along with cholesterol and other fats. Evidence that low-density lipoprotein oxidation plays a role in the development of atherosclerosis led scientists to investigate the role of antioxidant compounds like carotenoids in the prevention of cardiovascular disease (Kritchevsky 1999). The results of several prospective studies indicate that people with higher intakes of carotenoids-rich fruits and vegetables are at lower risk of cardiovascular disease (Sahyoun et al. 1996; Rimm et al. 1995; Gaziano et al. 1995; Osganian et al. 2003), it is not yet clear whether this effect is a result of carotenoids or other factors associated with diets high in carotenoids-rich fruits and vegetables.

Degeneration of the macula, the center of the eye's retina, is the leading cause of blindness in older adults. Unlike cataracts, in which the diseased lens can be replaced, there is no cure for age-related macular degeneration (AMD). Therefore, efforts are aimed at disease prevention or delaying the progression of AMD. The only carotenoids found in the retina are lutein and zeaxanthin. Lutein and zeaxanthin are present in high concentrations in the macula, where they are efficient absorbers of blue light. By preventing a substantial amount of the blue light entering the eye from reaching the underlying structures involved in vision, lutein and zeaxanthin may protect against light-induced oxidative damage, which is thought to play a role in the pathology of age-related macular degeneration (Snellen et al. 2002; Krinsky et al. 2003). Epidemiological studies provide some evidence that higher intakes of lutein and zeaxanthin are associated with lower risk of AMD (Mares-Perlman et al. 2002). To date, the available scientific evidence suggests that consuming at least 6 mg/day of dietary lutein and zeaxanthin from fruits and vegetables may decrease the risk of age-related macular degeneration (Seddon et al. 1994; Mares-Perlman et al. 2001, 2002). Four large prospective studies found that men and women with the highest intakes of foods rich in lutein and zeaxanthin, particularly spinach, kale, and broccoli, were 18-50 percent less likely to require cataract extraction (Brown et al. 1999; Chasan-Taber et al. 1999) or develop cataracts (Lyle et al. 1999; Christen et al. 2003; Moeller et al. 2008).

Phytates

Until recently, phytates were considered to be antinutrients since they prevented the absorption of other nutrients. Although they are not toxic and consuming them does not cause serious changes in our body, they were regarded negatively due to their ability to bind minerals in the intestine, such that the absorption of certain minerals, such as iron, calcium and magnesium was reduced throughout the body and the benefit received from these nutrients, which are fundamental to our health was less, which in the case of iron, could result in anaemia. Despite having been questioned, this view has changed and current opinion is that, in the correct proportions, phytates can play a beneficial role in our health. Once they have been absorbed, they can exert a biological effect, either inside or outside the intestine. If the phytic acid binds to lead or other metals, which are harmful to the body such as cadmium, it helps to detoxify it because it prevents it from assimilating in the blood and facilitates their elimination in our faeces without passing through the bloodstream from the intestine. Otherwise, they can cause irreversible damage to the central nervous system. Phytates' ability to bind themselves to other elements is highly beneficial for the human body since it helps to prevent the appearance of conditions such as diabetes, heart disease and kidney stones (Jariwalla 2001).

Inositol hexaphosphate (IP (6)) is a naturally occurring polyphosphorylated carbohydrate, abundantly present in many plant sources and in certain high-fiber diets, such as cereals and legumes. In addition to being found in plants, IP(6) is contained in almost all mammalian cells, although in much smaller amounts, where it is important in regulating vital cellular functions such as signal transduction, cell proliferation, and differentiation. For a long time IP (6) has been recognized as a natural antioxidant. Recently IP (6) has received much attention for its role in cancer prevention and control of experimental tumor growth, progression, and metastasis. In addition, IP(6) possesses other significant benefits for human health, such as the ability to enhance immune system, prevent pathological calcification and kidney stone formation, lower elevated serum cholesterol, and reduce pathological platelet activity (Vucenik and Shamsuddin 2003; Vucenik and Shamsuddin 2006). Specifically, the interaction of phytic acid with certain types of protein in the large intestine can help to reduce the activity of the bacterial enzymes involved in developing cancer of the colon. Furthermore, it binds with cholesterol and triglycerides, reducing their absorption and, consequently, their concentration in the blood, and also helps to control the rhythm of intestinal evacuation. Likewise, phytates prevent the formation of oxalate salts in the kidneys, which are responsible for forming kidney stones.

Polyphenols

Plant polyphenols, a large group of natural antioxidants, are serious candidates in

explanations of the protective effects of vegetables and fruits against cancer and cardiovascular diseases. Epidemiologic studies are useful for evaluation of the human health effects of long-term exposure to physiologic concentrations of polyphenols, but reliable data on polyphenols contents of foods are still scarce. Polyphenols occur in all plant foods and contribute to the beneficial health effects of vegetables and fruit. Their contribution to the antioxidant capacity of the human diet is much larger than that of vitamins. The total intake of polyphenols in a person's diet could amount to 1 gram a day, whereas combined intakes of beta-carotene, vitamin C, and vitamin E from food most often is about 100 mg a day. Phenolic acids account for about one third of the total intake of polyphenols in our diet, and flavonoids account for the remaining two thirds. (Williamson and Manach 2005).

Fruit and beverages such as tea and red wine represent the main sources of polyphenols. Despite their wide distribution, the healthy effects of dietary polyphenols have come to the attention of nutritionists only in the last years. The main factor responsible for the delayed research on polyphenols is the variety and the complexity of their chemical structure. Emerging findings suggest a large number of potential mechanisms of action of polyphenols in preventing disease, which may be independent of their conventional antioxidant activities. Isoflavones (genistein and daidzein, found in soy) have significant effects on bone health among postmenopausal women, together with some weak hormonal effects. Monomeric catechins (found at especially high concentrations in tea) have effects on plasma antioxidant biomarkers and energy metabolism. Procyanidins (oligomeric catechins found at high concentrations in red wine, grapes, cocoa, cranberries, apples, and some supplements such as Pycnogenol) have pronounced effects on the vascular system, including but not limited to plasma antioxidant activity. Quercetin (the main representative of the flavonol class, found at high concentrations in onions, apples, red wine, broccoli, tea, and Ginkgo biloba) influences some carcinogenesis markers and has small effects on plasma antioxidant biomarkers in vivo, although some studies failed to find this effect. Compared with the effects of polyphenols in vitro, the effects in vivo, although significant, are more limited (Williamson and Manach 2005).

Harper et al. (2009) showed that Genistein, resveratrol, and the high-dose combination treatments suppressed prostate cancer. Polyphenol treatments decreased cell proliferation and insulin-like growth factor-1 (IGF-1) protein expression in the prostate. In addition, genistein as a single agent induced apoptosis and decreased steroid receptor coactivator-3 in the ventral prostate. Genistein and resveratrol, alone and in combination, suppress prostate cancer development in the SV-40 Tag model. Regulation of SRC-3 and growth factor signaling proteins are consistent with these nutritional polyphenols reducing cell proliferation and increasing apoptosis in the prostate. The health benefits of Epigallocatechin-3-gallate, one of the most abundant and widely studied catechin found in green tea (*Camellia sinensis*) catechins are becoming increasingly recognised. Amongst the proposed benefits are the maintenance of endothelial function and vascular homeostasis and an associated reduction in atherogenesis and cardiovascular disease risk (Moore et al. 2009). Atherogenic dyslipidaemia associated with a pro-inflammatory pro-thrombotic state in metabolic syndrome and related risk of fatty liver, arthritis, neurodegenerative disorders and certain types of cancers are ideal therapeutic targets for bioactive phytochemicals, particularly flavonoids and tanins which can combat oxidative stress induced damage at a sub-cellular level (Soory 2009).

Sulphur compounds

Currently reliance on natural products is gaining popularity to combat various physiological threats including oxidative stress, cardiovascular complexities, cancer insurgence, and immune dysfunction. The use of traditional remedies may encounter more frequently due to an array of scientific evidence in their favor. Garlic (*Allium sativum*) holds a unique position in history and was recognized for its therapeutic potential. Recent advancements in the field of immunonutrition, physiology, and pharmacology further explored its importance as a functional food against various pathologies. Extensive research work has been carried out on the health promoting properties of garlic, often referred to its sulfur containing metabolites i.e. allicin and its derivatives. Garlic in its preparations are effective against health risks and even used as dietary supplements such as age garlic extract (AGE) and garlic oil etc. Its components/formulations can scavenge free radicals and protect membranes from damage and maintains cell integrity. It also provides cardiovascular protection mediated by lowering of cholesterol, blood pressure, anti-platelet activities, and thromboxane formation thus providing protection against atherosclerosis and associated disorders. Besides this, it possesses antimutagenic and antiproliferative properties that are interesting in chemopreventive interventions (Butt et al. 2009).

Non-pharmacological treatment options for hypertension have the potential to reduce the risk of cardiovascular disease at a population level. Animal studies have suggested that garlic reduces blood pressure, but primary studies in humans and non-systematic reviews have reported mixed results. Reid et al. (2008) meta-analysis revealed that garlic preparations are superior to placebo in reducing blood pressure in individuals with hypertension. Garlic reduced systolic blood pressure (SBP) by 16.3 mm Hg (95% CI 6.2 to 26.5) and diastolic blood pressure (DBP) by 9.3 mm Hg compared with placebo in patients with elevated SBP. Meta-analysis suggests that garlic is associated with blood pressure reductions in patients with an elevated SBP although not in those without elevated SBP (Reinhart et al. 2008).

Garlic has been used for centuries for treating various ailments, and its consumption is said to reduce cancer risk and its extracts and components effectively block experimentally induced tumors (Hirsch et al. 2000; Ried et al. 2008). The study conducted by Oommen et al. (2004) demonstrated allicin-induced apoptosis of cancer cells are novel since allicin has not been shown to induce apoptosis previously. This study also provides a mechanistic basis for the antiproliferative effects of allicin and partly account for the chemopreventive action of garlic extracts reported by earlier workers.

Glucosinolates (GLSs) are found in *Brassica* vegetables. Examples of these sources include cabbage, brussels sprouts, broccoli, cauliflower and various root vegetables (e.g. radish and turnip). A number of epidemiological studies have identified an inverse association between consumption of these vegetables and the risk of colon and rectal cancer. Animal studies have shown changes in enzyme activities and DNA damage resulting from consumption of brassica vegetables or isothiocyanates, the breakdown products of GLSs in the body (Verkerk et al. 2009). Broccoli consumption mediates a variety of functions including providing antioxidants, regulating enzymes and controlling apoptosis and cell cycle. The organosulfur chemicals namely glucosinolates and the S-methyl cysteine sulphoxide found in broccoli in concert with other constituents such as vitamins E, C, K and the minerals such as iron, zinc, selenium and the polyphenols namely kaempferol, quercetin glucosides and isorhamnetin are presumably responsible for various health benefits of broccoli (Vasanthi et al. 2009).

Potassium

Potassium intake prevents from ailments like stroke, blood pressure, anxiety and stress, muscular strength, metabolism, heart and kidney disorders, water balance, electrolytic functions, nervous system and other general health problems. Until recently, humans consumed a diet high in potassium. However, with the increasing consumption of processed food, which has potassium removed, combined with a reduction in the consumption of fruits and vegetables, there has been a large decrease in potassium intake which now, in most developed countries, averages around 70 m mol day^{-1}, i.e. only one third of our evolutionary intake. Much evidence shows that increasing potassium intake has beneficial effects on human health. Epidemiological and clinical studies show that a high-potassium diet lowers blood pressure in individuals with both raised blood pressure and average population blood pressure. Prospective cohort studies and outcome trials show that increasing potassium intake reduces cardiovascular disease mortality. This is mainly attributable to the blood pressure-lowering effect and may also be partially because of the direct effects of potassium on the cardiovascular system. A high-potassium diet may also prevent or at least slow the progression of renal disease. An increased potassium intake lowers urinary calcium excretion and plays an important role in the management of hypercalciuria and kidney stones and is likely to decrease the risk of osteoporosis. Low serum potassium is strongly related to glucose intolerance, and increasing potassium intake may prevent the development of diabetes that occurs with prolonged treatment with thiazide diuretics (Feng et al. 2008**).** Dietary intake of Potassium among Indians is one tenth of what is recommended. Therefore consuming various varieties of fruit and vegetables will augment the potassium levels effectively.

Other minerals

Boron, chromium, manganese, nickel, tin, vanadium, molybdenum, arsenic, lithium, aluminium, strontium, cesium and silicon are regarded as new trace elements in the sense that they have only recently been considered essential in human diets. These elements are the subject of exciting research in animals, particularly ruminants, where they have been shown to be essential in one or more species. For example, ruminants feeding on grass grown in soil where molybdenum levels are abnormally high have demonstrated an increased tendency to exhibit copper deficiency. However, for many of these new trace elements (e.g., Mn) there is no evidence that abnormally low or high dietary intakes cause substantial nutritional problems in human populations (Weisell 1991).

Conclusions

Nutrition science and the quest to improve human diet have undergone a quiet but major transition over the last 50 years. The first half of the 20th century was centered on the discovery and characterization of essential nutrients, vitamins, amino acids, and cofactors that were indispensable constituents of a healthy diet. These discoveries greatly influenced the focus of applied nutrition, which centered first on defining the minimum needs of essential nutrients in humans, and second in defining diets that provided those minimum amounts needed to maintain health. In the second half of the 20th century, environmental factors began to gain prominence as important determinants of human health. It witnessed the increasing influence of nutritional epidemiology in discovering these diet–health associations, and deciphered the mystery by performing some of the unique experiments on human beings. Some of the phytochemicals such as flavonoids, phenolic acids, carotenoids, sulphur compounds, minerals, trace elements showed beneficial biological activity in chronic degenerative diseases. These should be considered along with the known nutrients for sustaining human health. Until recently, the role of nutrients in preventing chronic diseases was not systematically considered in defining dietary recommendations.Therefore, there is urgent need to look in to the recommended dieatry allownaces for these emerging nutrients for various physcilogical groups.

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Impact of potassium nutrition on postharvest fruit quality: Melon (*Cucumis melo* L) case study

Gene E Lester • John L Jifon • Donald J Makus

Abstract Among the many plant mineral nutrients, potassium (K) stands out as a cation having the strongest influence on quality attributes that determine fruit marketability, consumer preference, and the concentration of critically important human-health associated phytonutrients. However, many plant, soil, and environmental factors often limit adequate uptake of K from the soil in sufficient amounts to satisfy fruit K requirements during development to optimize the aforementioned quality attributes. The objectives of this review are 1) to summarize published study abstracts on the effects of soil and/or foliar K fertilization as well as diverse K forms, on fruit phytonutrient concentrations; and 2) to illustrate the important role of K forms on fruit quality with a case study of *Cucumis melo* L (muskmelon) fruit produced with optimal soil applied K. The muskmelon studies will compare commercial sources (forms) of K applied to examine seasonal effects (spring vs. autumn) and the number of foliar K applications during fruit development on fruit marketability (maturity, yield, firmness, soluble solids, sugars, relative sweetness), consumer preference attributes (sugar content, sweetness, texture), and phytochemical concentrations (K, ascorbic acid, and b-carotene concentrations). Numerous studies have consistently demonstrated that specific K fertilizer forms, in combination with specific application regimes, can improve fruit quality attributes. Potassium fertilizer forms in order of effectiveness (Glycine (Gly)-complexed K = $K_2SO_4 \geq$ KCl > no K > KNO_3) when applied wet (foliar or hydroponic) vs. dry (soil) were generally superior in improving fruit marketability attributes, along with many human-health nutrients. The muskmelon case study demonstrated that two K

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forms: Gly-complexed K and K_2SO_4, combined with a silicone-based surfactant, applied weekly, as a foliar spray, during fruit development, from both autumn and spring-grown plants, had the greatest impact on improving fruit marketability attributes (maturity, yield, firmness, and sugars), as well as fruit quality attributes (human-health bioactive compounds K, ascorbic acid, and β-carotene). Among several foliar applied K salts studied under field conditions so far, salts with relatively low salt indices appeared to have the greatest impacts on fruit quality when applied during the mid- to late-season fruit development periods.

Keywords Fruit • foliar application • human health • marketability • potassium fertilizers • sugar • vitamins • yield

Introduction

Potassium (K) is an essential plant mineral element (nutrient) having a significant influence on increasing many human-health related quality compounds in fruits and vegetables (Usherwood, 1985). Although K is not a constituent of any organic molecule or plant structure, it is involved in numerous biochemical and physiological processes vital to plant growth, yield, quality and stress (Marschner, 1995; Cakmak, 2005). In addition to stomatal regulation of transpiration and photosynthesis, K is also involved in photophosphorylation, transportation of photoassimilates from source tissues via the phloem to sink tissues, enzyme activation, turgor maintenance, and stress tolerance (Usherwood, 1985; Doman and Geiger, 1979; Marschner, 1995; Pettigrew, 2008). Adequate K nutrition has also been associated with increased yields, fruit size, increased soluble solids and ascorbic acid concentrations, improved fruit color, increased shelf life, and shipping quality of many horticultural crops (Geraldson 1985; Lester et al. 2005, 2006; Kanai et al. 2007).

Even though K is abundant in many soils, the bulk of soil K is unavailable to plants, in part, because the pool of plant-available K is much smaller compared to the other forms of K in the soil. Potassium exists in several forms in the soil such as mineral K (90-98% of total), nonexchangable K, exchangeable K, and dissolved or solution K (K^+ ions), and plants can only directly take up solution K (Tisdale et al. 1985). Uptake in turn depends on numerous plant and environmental factors (Tisdale et al. 1985; Marschner, 1995; Brady and Weil 1999). For instance, adequate soil moisture supply is necessary to facilitate diffusion of K (which usually accounts for > 75% of K movement) to plant roots for uptake. Mass flow, which also accounts for some soil K transport, also requires sufficient water in the soil. Skogley and Haby (1981) found that increasing soil moisture from 10 to 28% more than doubled total soil K transport. Therefore, soil moisture deficits can limit soil K transport as well as uptake into the plant, thereby causing K deficiency.

Soil properties also have a strong influence on K availability. For instance, clay soils typically have high K-fixing capacities and thus often show little response to soil-applied K fertilizers because much of the available K quickly binds to clays (Tisdale et al. 1985; Brady and Weil 1999). Such K fixation can help reduce leaching losses, and be beneficial in the long-term as storage reservoirs of K for subsequent crops. Sandy soils, on the other hand tend to have a low K supplying power because of their low cation exchange capacities.

In calcareous soils, Ca^{2+} ions tend to exist in high concentrations and dominate clay surfaces, and even though this can limit K sorption and increase solution K, high concentrations of cationic nutrients (particularly Ca^{2+} and Mg^{2+}) tend to limit K uptake by competing for binding sites on root surfaces. Consequently, crops grown on highly calcareous soils can show K-deficiency symptoms even though the soil test may report sufficient K (Havlin et. al. 1999).

Potassium uptake also depends on plant factors, including genetics and developmental stage (vegetative versus reproductive stages; Rengel et al. 2008). In many fruiting species, uptake occurs mainly during vegetative stages, when ample carbohydrate supply is available for root growth and uptake processes. Competition for photoassimilates between developing fruits and vegetative organs during reproductive growth stages can limit root growth/activity and K uptake. Under such conditions, increasing soil K fertilization may not be enough to alleviate this developmentally-induced deficiency partly because of reduced root growth/activity during reproductive development and also because of competition from other cations for binding sites on roots (Marschner 1995).

In the literature, much confusion exists regarding the benefit of K fertilization due to different K forms utilized, soil vs. foliar applications, the environment (season), plus frequency of applications during fruit growth and development stages. This review will (1) summarize some of the published abstracts on K fertilization of several fruit crops, and (2) illustrate the influence of adequate K nutrition on fruit quality with a case study of supplemental foliar K fertilization of *Cucumis melo* L (muskmelon) grown on soil with seemingly adequate K content. Special attention is given to the effectiveness (comparison) of various K fertilizer sources, and soil vs. foliar application on fruit quality.

Fruit studies comparing K sources

Although many examples have been reported on the positive effects of K fertilization improving fruit disease control, yield, weight, firmness, sugars, sensory attributes, shelf-life, and human bioactive compound concentrations, the scientific literature also contains examples of studies with conflicting results of the beneficial effects of K fertilization on fruit quality (Table 1). These conflicting results cannot be resolved, but they can be explained by differences in modes of fertilization [soil applied (dry) vs. foliar, fertigation or hydroponic applied (wet)], and differences in forms of K fertilizer e.g. Glycine-complexed K, versus K_2SO_4, KCl, or KNO_3 from K fertilization. A review of published abstracts (Table 1), spanning the last twenty years, eight particular studies [apple (*Malus X Domestica;* Hassanloui, et al. 2004), cucumber (*Cucumis sativus;* Umamaheswarappa and Krishnappa 2004), mango (*Mangifera indica;* Rebolledo-Martinez et al. 2008), pear (*Prunus communis;* Johnson et al. 1998), bell pepper (*Capsicum annuum;* Hochmuth et al. 1994), strawberry (Fragaria X ananassa; Albregts et al. 1996), and watermelon (*Citrullus lanatus;* Locascio and Hochmuth 2002; Perkins-Veazie et al. 2003)] stand out, because of their conclusions: there is 'little or no change' (i.e. improvement) from K fertilization on fruit quality. However, except for the apple study, these studies have a common denominator in that potassium was applied directly to the soil and in many cases little information was given regarding timing of application with regard to crop phenology or soil chemical and physical properties such as pH, calcium and magnesium contents, and textures (sandy vs. clay). These properties are known to influence soil nutrient availability and plant uptake, and soil fertilizer K additions under such conditions may have little or no effect on uptake, yield and fruit quality (Tisdale et al. 1985; Brady and Weil 1999). In a number of studies involving several fruiting crops (e.g. cucumber, mango, and muskmelon) where soil-applied fertilizer K was compared to foliar K applications, the latter approach consistently resulted in improved fruit quality attributes whereas the former approach generally had little or no effects (Demiral and Koseoglu 2005; Lester et al. 2005; Lester et al. 2006; Jifon and Lester 2009; Table 1). Furthermore, in studies where several fertilizer K salts were evaluated, fruit quality improvements appeared to depend on timing of application as well as fertilizer K formulation. For instance, when mid- to-late season soil or foliar K applications were made using KNO_3 there were little or no improvements in fruit marketable or human-nutritional quality attributes and in some instances, these attributes were actually inferior compared to fruit from control plots (Jifon and Lester 2009).

Foliar Fertilization with different K salts: Case studies with muskmelon (*Cucumis melo* L.)

As discussed above, plant and soil factors can limit soil-available, as well as plant uptake of K even though soil tests may report sufficient K. This situation is particularly acute for crops grown on highly calcareous soils whereby such uptake limitations can lead to K-deficiency symptoms, reduced yield and poor quality. In such cases where soil-applied fertilizers would be ineffective, due to high fixation, the only way to improve plant K uptake has been through foliar application of water-soluble K fertilizers, such as potassium chloride (KCl) or potassium nitrate

Table 1 Review of published abstracts on the influence of potassium (K): effects by crop, K application, and K form on fruit attributes

Crop	K application	K form[a]	Attributes (improved)[b]	Reference[c]
Apple (*Malus X domestica*)	Soil	KCl; K_2SO_4; K_2SO_4	Color, firmness, sugar; Size, color, firmness, sugars; Wt. yield, firmness, sugars	(Nava et al. 2009) ; El-Gazzar (2000); Attala (1998)
Apple	Foliar	Unknown; KCl	Size, color, firmness, sugars; No change	Wojcik (2005); (Hassanloui et al. 2004)
Banana (*Musa sp.*)	Soil	Unknown; KCl	Quality; Size, sugars, acid	Naresh (1999); (Suresh & Hasan 2002)
Citrus (*Citrus sinesis*)	Foliar	KCl, KNO_3;, unknown; K_2SO_4	No change; Yield, quality; Quality	Haggag (1990); (Dutta et al. 2003); (Shawky et al. 2000)
Citrus (*Citrus reticulata*)	Soil	Unknown; Unknown	Yield, quality; Quality, shelf-life	(Lin et al. 2006); (Srivastava et al. 2001)
Citrus (*Citrus reticulata*)	Foliar	KCl >KNO_3	Peel thickness, quality	(Gill & Singh 2005)
Cucumber (*Cucumis sativus*)	Soil	K_2SO_4 > KCl; KCl	Amino acids, quality; No change	(Guo et al. 2004); (Umamaheswarappa & Krishnappa 2004)
Cucumber	Foliar	KCl >KNO_3	"Quality", disease tolerance	(Magen et al. 2003)
Grapes (*Vitis vinifera*)	Soil	K_2SO_4	"Quality", sensory	(Sipiora et al. 2005)
Guava (*Psidium guajava*)	Soil	Unknown	Yield, weight, "quality"	(Ke & Wang 1997)
Guava	Foliar	K_2SO_4 > KCl	Acidity, "quality"	Dutta (2004)
Kiwifruit (*Actinidia deliciosa*)	Soil	K_2SO_4 > KCl	Firmness, acid, grade	He (2002)
Litchi (*Litchi chinensis*)	Foliar	KNO_3	Wt., yield,	(Ashok & Ganesh 2004)
Mango (*Mangifera indica*)	Soil	KNO^3	No change	Simoes (2001)

Crop	K application	K form[a]	Attributes (improved)[b]	Reference[c]
Mango	Foliar	KNO_3; Unknown	No effect; Texture, flavor, color, shelf-life	(Rebolledo-Martinez et al. 2008); Shinde (2006)
Muskmelon *(Cucumis melo)*	Soil	Unknown	Yield	(Demiral & Koseoglu 2005)
Muskmelon	Foliar	Gly-amino-K; Gly-amino-K > KCl; Gly-amino-K = $K_2 SO_4$ > KCl > KNO_3	Firmness, vitamins; Firmness, sugars, vitamins; Firmness, vitamins, sugars, yield, marketable fruit	(Lester et al. 2006); Lester (2006); Jifon & Lester (2009)
Nectarine *(Prunus persica)*	Soil	Unknown	Firmness, shelf-life, reduced cracking	(Zhang et al. 2008)
Okra *(Abelmoschus esculentus)*	Foliar	Naphthenate-K	Chlorophyll, protein, carotene	(Jahan et al. 1991)
Passionfruit *(Passiflora edulis)*	Hydroponic	$K_2 SO_4$	Yield, seed number, "quality"	(Costa-Araujo et al. 2006)
Papaya *(Carica papaya)*	Soi	Unknown	Weight, sugars, "quality"	Ghosh & Tarai (2007)
Pears *(Prunus communis)*	Soi	$K_2 SO_4$	No change	(Johnson et al. 1998)
Phalsa *(Grewia subinaequalis)*	Foliar	$K_2 SO_4$	Size, wt., "quality"	(Singh et al. 1993)
Pepper *(Capsicum annuum)*	Soil	KCl; $K_2 SO_4$; $K_2 SO_4$ > KNO_3; $K_2 SO_4$	Little change; Pungency, "quality"; Pungency, yield, wt.; "quality"	(Hochmuth et al. 1994): (Ananthi et al. 2004); (Golcz et al. 2004); El-Masry (2000)
Pepper	Hydroponics	KNO_3	No change	(Flores et al. 2004)

Crop	K application	K form[a]	Attributes (improved)[b]	Reference[c]
Pineapple *(Ananas comosus)*	Soil	KCl	Vit. C, and reduced internal browning	(Herath et al. 2000)
Pomegranate *(Punica granatum)*	Foliar	$K_2 SO_4$ > KCl	Growth, yield, "quality"	Muthumanickam & Balakrishnamoorthy (1999)
Strawberry *(Fragaria X ananassa)*	Soil; Fertigation	KCl; KCl >KNO_3	No change; "quality"	(Albregts et al. 1996); (Ibrahim et al. 2004)
Strawberry	Hydroponics	$K_2 SO_4$	Yield , total quality	(Khayyat et al. 2007)
Tomato *(Lycopersicon esculentum)*	Soil	KCl; $K_2 SO_4$; $K_2 SO_4$;	Lycopene; "quality"; Yield, earliness, quality	(Taber et al. 2008); (Si et al. 2007); Hewedy (2000)
Tomato	Fertigation/ soilless	KCl >KNO_3; KCl >KNO_3; $K_2 SO_4$; Unknown; Unknown	Appearance, quality; Yield, "quality"; Carotenoids, vit.E, Antioxidants; Lycopene; "quality"	Chapagain & Wiseman (2003); Chapagain & Wiseman (2004); (Fanasca et al. 2006); (Li et al. 2006); (Yang et al. 2005)
Tomato	Foliar	Unknown	Growth, protein, vit. C, sugar, acid	(Li et al. 2008)
Vegetables	Soil	$K_2 SO_4$ > KCl	Dry wt., vit. C	(Ni et al. 2001)
Watermelon *(Citrullus lanatus)*	Soil	KCl KCl	No change; No change	Locascio & Hochmuth (2002); (Perkins-Veazie et al. 2003)

[a]Forms from different studies are separated by a semi-colon; K form attributing to improved quality greater than another K form is indicated by the > symbol; [b]Attributes from different studies are separated by a semicolon, the word "quality" indicates the authors' listed no specific attributes, or the attributes were too numerous to list, [c]References from different studies are separated by a semi-colon

(KNO_3). Controlled environment studies have indeed shown that supplementing soil-derived K supply with foliar K applications during the fruit development period can improve fruit quality and that differences may exist among K compounds for foliar feeding (Lester et al. 2005; 2006). To further explore the degree to which differences among some K salts may influence fruit quality, field studies were conducted near Weslaco, TX using a netted muskmelon (*Cucumis melo* L.) variety 'Cruiser'. Soils in this important fruit-producing region are predominantly calcareous with free calcium carbonate ($CaCO_3$), which tends to buffer soil pH to around 7.5 to 8.5. Base saturation is generally ~100%, and cation exchange is dominated by calcium. Average pre-plant soil concentrations of major cations were 7300, 660, 440, and 190 mg kg^{-1} for Ca, K, Mg and Na respectively. All studies were conducted during the spring (February-May) growing season following standard commercial muskmelon production practices for this region (Dainello 1996). Foliar K treatments (Fig.1) were applied weekly (between 0500 and 0800 a.m.) starting at fruit set, and continued till fruit maturation using K from various sources namely: potassium chloride (KCl), potassium nitrate (KNO_3), potassium sulfate (K_2SO_4), Gly-complexed K (glycine amino acid complexed K - Potassium Metalosate™, 20% K; Albion Laboratories, Inc, Clearfield, Utah), monopotassium phosphate (PeaK™, 24% K, Rotem BKG LLC, Ft Lee, NJ), and potassium thiosulfate (KTS™, 20% K, Tessenderlo Kerley Inc., Phoenix, AZ). Treatment solutions were formulated to supply the equivalent of ~4 kg K ha^{-1} per week and each solution contained a non-ionic surfactant (Silwet L-77 at 0.3% v/v; Helena, Collierville, TN).

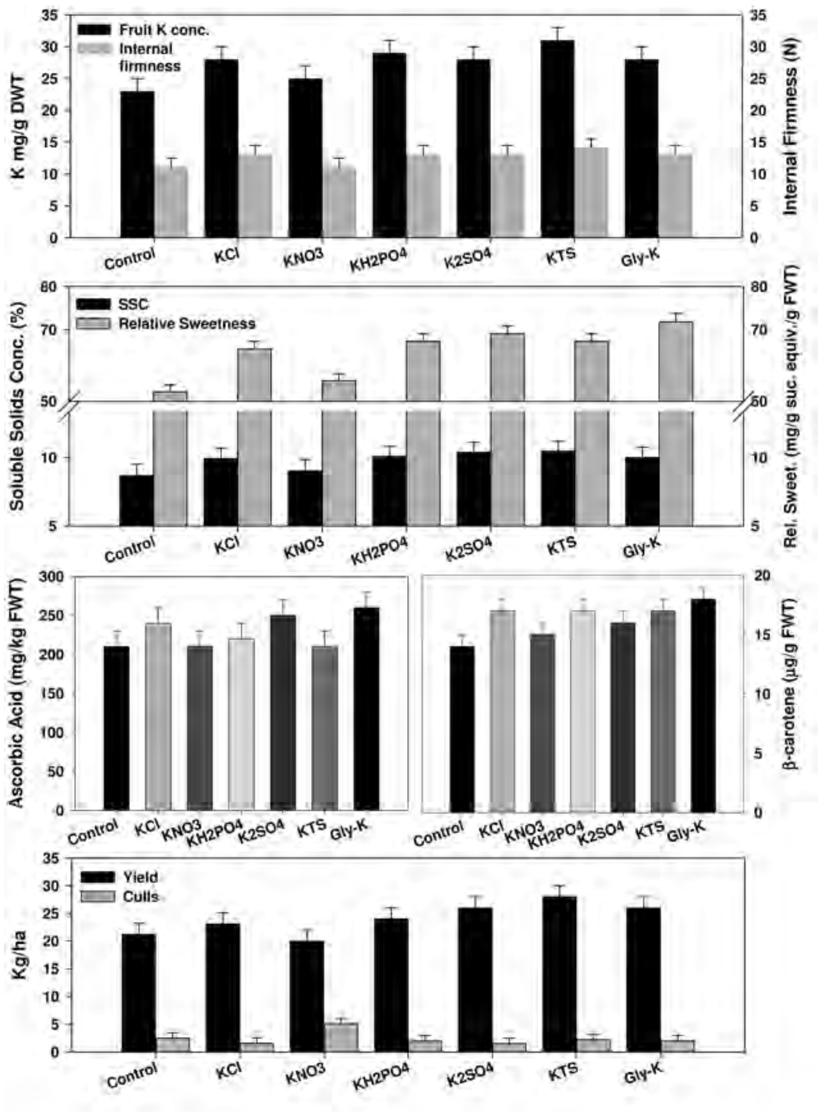
Leaf K concentrations measured during the fruit maturation period were significantly lower (~13 g kg^{-1}) than the values measured before fruit set (~37 g kg^{-1}). Leaf K concentrations were also lower than the recommended sufficiency ranges (20-40 g kg^{-1}; Hochmuth and Hanlon 1995), even though pre-plant soil analysis indicated very high soil K concentrations (>600 mg kg^{-1}). At fruit maturity, tissue (leaf, petiole, stem and fruit) K concentrations of foliar K-treated plants were on average ~19% higher than those of control plants. This observation suggests that plant K uptake from this calcareous soil was not sufficient to maintain tissue K concentrations within sufficiency levels, and that the K supplying power of this soil may be low even though pre-plant soil K content was high. The low K supplying capacity of this soil is further indicated by the high pH and high Ca and Mg concentrations since these conditions are known to suppress soil K availability and plant uptake (Marschner 1995; Brady and Weil 1999). Fruit quality parameters (soluble solids concentration, total sugars, sweetness, and the phytochemical compounds - ascorbic acid and beta-carotene) responded positively to foliar K applications (Fig. 1). However, no clear trends were apparent with regard to the most suitable salt for all quality parameters except for KNO_3 whose effects were nearly always statistically similar to those of the control treatments. The lack of significant differences between controls and KNO_3-treated plants was probably related to timing of treatment applications with respect to crop phenology. Treatments were applied during the reproductive growth stages (mid- to late-season), and foliar fertilization with KNO_3 significantly increased leaf N concentrations (~30%) compared to the other K salts; the resulting stimulation of vegetative growth at the expense of roots and fruits probably accounted for the marginal effect on fruit quality through competition for assimilates (Way and While 1968; Davenport 1996; Neuweiler 1997; Keller et al. 1999; Wade et al. 2004). Fruit mesocarp tissue firmness, a good indicator of shipping quality, texture and shelf life (Harker et. al. 1997), was improved by foliar K applications. This may be related to increased tissue pressure potential (Lester et al. 2006). Foliar K-treated plots had slightly higher yields (Fig. 1), however, this effect was only significant in one of the three years, and with one K salt (potassium thiosulfate). Additionally, the average number of cull fruit with defects such as poor external rind (net) development or small size was generally higher in plots treated with foliar KNO_3 than in plots treated with the other K forms (Fig. 1).

In addition to plant and environmental factors, critical properties of potential K salts for foliar nutrition are solubility, salt index (SI) and point of deliquescence (POD). A suitable balance among these properties is required to maximize nutrient absorption into plant tissues and to minimize phytotoxicity effects. Highly soluble salts are preferred since this means faster cuticular penetration and smaller volumes of solution needed for application. The salt index of a fertilizer material is defined as the ratio of the increase in solution osmotic pressure produced by the fertilizer material to that produced by the same mass of $NaNO_3$ (Mortvedt, 2001). The SI gives an indication of which fertilizer salts (usually those with higher SI) are most likely to cause injury and compares one fertilizer formulation with others regarding the osmotic (salt) effects (Mortvedt, 2001). The SI of some common K salts are, KCl, 116; KH_2PO_4, 8.4; K_2SO_4, 43; potassium thiosulfate, 68 (Mortvedt, 2001).

A common production problem not observed in this study, which is likely temperature related, is the foliar 'burning' effect, which is frequently observed when using foliar applied salts such as KCl (Swietlik and Faust, 1984). Burning of leaves occurs when salts accumulate on the surface and are not absorbed. Rates of absorption are highest when relative humidity is 80% or higher (Schonherr and Luber, 2001). In this field study leaf 'burn' symptoms were not observed with any of the treatments, in part, because all treatments were applied between 0500 and 0800 when high air relative humidities, (>80%), low air temperatures (<25°C) and low wind speeds (< 0.45 m s^{-1}) prevailed.

Point of deliquescence of a foliar fertilizer salt determines the rate at which the applied salt is absorbed by plant tissues. Point of deliquescence is the humidity

Fig. 1 Effects of various K fertilizer sources (potassium chloride - KCL, potassium nitrate - KNO_3, potassium sulfate - K_2SO_4, gylcine amino acid potassium - Gly –K, monopotassium phosphate - KH_2PO_4, and potassium thiosulfate - KTS) foliar applied weekly to field-grown, fruit-bearing muskmelon plants during fruit development on various marketability and quality attributes of fruit. All plants had sufficient soil fertilization. Relative sweetness = 1.8 (mg/ g FWT fructose) + 0.7 (mg/g FWT glucose) + 1.0 (mg/g FWT sucrose). Data are means ± SD and are separated by the LSMEANS procedure of SAS (Statistical Analysis System, Cary, NC, USA) at $P \leq 0.05$ (Jifon and Lester 2008)



over a saturated salt solution containing solid salt (Schönherr and Luber 2001). If air humidity is higher than the POD, salts will remain dissolved in solution and absorption will proceed rapidly. However, when air humidity is below the POD (i.e. drier air), salts will re-crystallize, resulting in slower uptake and increasing the potential for salt injury. Reported POD values for some common K salts are K_2CO_3, 44%; KCl, 86%; KNO_3, 95%; and KH_2PO_4, 97% (Schönherr and Luber, 2001). Several studies have shown that phytotoxicity effects are common when compounds such as KCl, with high salt indices and relatively high point of deliquescence, are used and this is more pronounced when they are applied under conditions of high temperature and/or low air humidity (Schönherr and Luber, 2001).

K fertilizer application: Seasonal influence and silicone-based surfactant

Muskmelon fruit firmness (external - under the epidermis, at the equatorial region; and internal middle-mesocarp - at the equatorial plane, using a penetrometer) from autumn and spring fruit-bearing plants, sprayed with K, was higher than that of fruit from control plants (no foliar K) regardless of season, surfactant use, or K form (Fig 2). Similar beneficial effects of foliar K, from KH_2PO_4, on tomato fruit (*Lycopersicon esculentum* Mill.) firmness has been shown (Chapagain and Wiesman, 2004), but the mechanisms for improved firmness were not discussed. Increased melon fruit firmness from exogenously-applied K is not due to improved membrane integrity or cell wall stability, as is the case with exogenously-applied calcium (Lester and Grusak 1999), since K does not become part of any structural component of plant tissues as does Ca (Cooke and Clarkson 1992). The increase in melon fruit firmness resulting from foliar applied K is increased (more positive) fruit-tissue pressure potential (ψ_p) (Table 2). Mesocarp tissue ψ_p was significantly higher in all K-treated, compared to non-treated control fruits. Addition of surfactant increased the effect of foliar K application on mesocarp tissue ψ_p (+46% and +150% for Gly amino acid complexed K (Gly-K) and KCl, respectively), although surfactant use was not always associated with increased fruit firmness. A significant positive correlation was observed between fruit-tissue ψ_p and internal fruit firmness (r = 0.259; P = 0.01). The increased ψ_p of K-treated fruit, compared to controls, resulted, at least in part, from greater accumulation of other osmolytes (e.g. sugars; Fig. 2) in addition to increased K concentrations in fruit cells (Lester et al., 2006). Since there were no differences in tissue water potential (ψ_w), a more negative solute potential (ψ_s) resulted in higher ψ_p ($\psi_p = \psi_w - \psi_s$) values in K-treated, compared to control fruits (Lester et al. 2006). Pressure potential was found to be positively correlated with SSC (r = 0.232; P = 0.01), total sugars (r = 0.276), fruit sucrose and glucose concentrations (P = 0.05) (Lester et al. 2006). Positive correlations among tissue solute

Fig. 2 Effect of growing season (autumn or spring) and two sources of K (potassium chloride - KCL, gylcine amino acid potassium –Gly –K) with or without a silicon-based surfactant (S) foliar applied weekly to glasshouse-grown fruit-bearing muskmelon plants during fruit development on various marketability and quality attributes of fruit. All plants had sufficient soil fertilization. Relative sweetness = 1.8 (mg/ g FWT fructose) + 0.7 (mg/g FWT glucose) + 1.0 (mg/g FWT sucrose). Data are means $\pm$ SD and are separated by the LSMEANS procedure of SAS (Statistical Analysis System, Cary, NC, USA) at $P \leq 0.05$ (Lester et al. 2006)

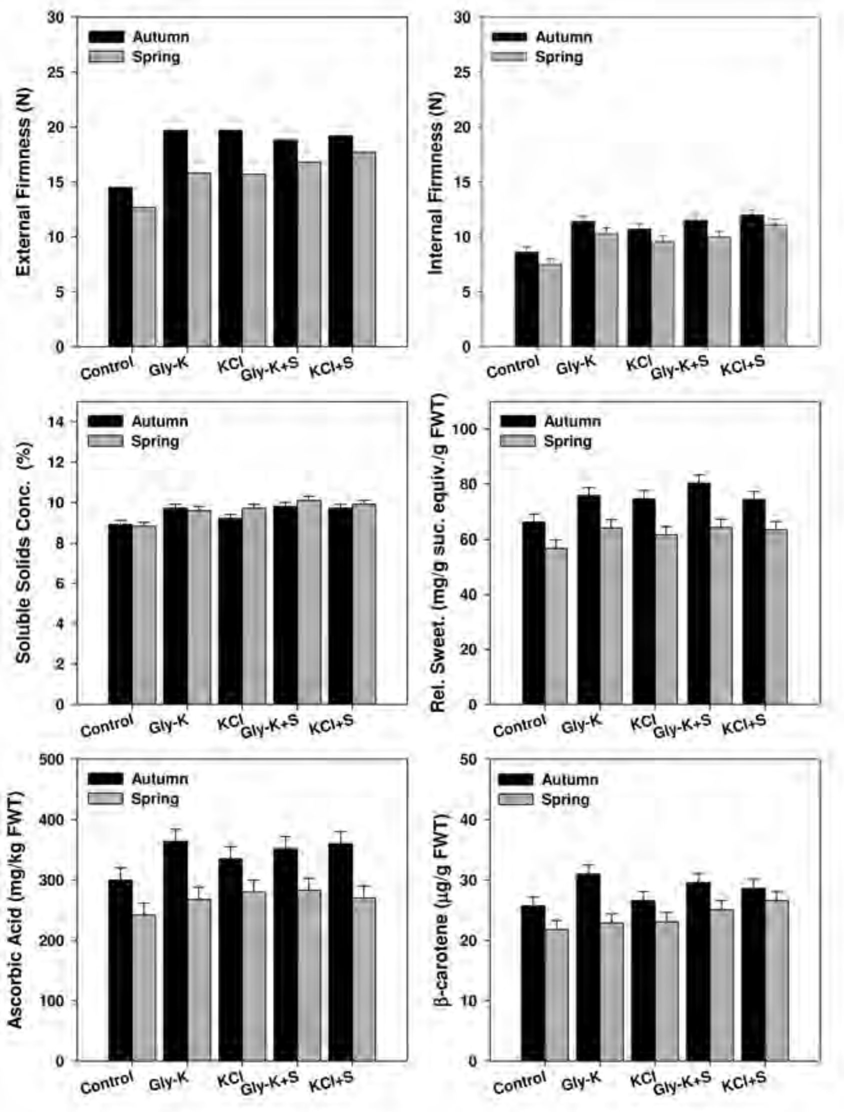


Table 2 Influence of weekly supplemental foliar K - glycine amino acid-potassium (Gly-K) and potassium chloride (KCl) applied with or without a surfactant (S), to fruit-bearing plants grown with adequate soil K concentrations, on muskmelon fruit tissue pressure potential (Lester et. al. 2006)

Treatment	Fruit Pressure ψ_p (MPa)[a]
Gly-K	-0.018b[b]
KCl	-0.034c
Gly-K +S	0.003a
KCl + S	0.011a
Control	-0.064d

[a] The more positive the pressure potential the firmer the fruit. [b] Means followed by the same letter are not significantly different by the LSMEANS procedure of SAS (Statistical Analysis System, Cary, NC, USA) at P< 0.05

concentration, turgor and firmness have also been reported for potato (*Solanum tuberosum* L.) tubers (Beringer et al. 1983) and apples (Tong et al. 1999).

Fruit sugars as measured by soluble solids concentrations and relative sweetness were higher in K-treated compared to control fruit in both autumn and spring grown fruit (Fig. 2). Fruits from plants treated with Gly-K also tended to have slightly greater soluble solids concentrations and relative sweetness levels than those treated with KCl regardless of silicone-based surfactant use or season. Previous studies on supplemental K fertilization have reported a variety of responses including an increase in fruit sugar levels (e.g. Chapagain and Wiesman 2004; Daugaard and Grauslund 1999; Johnson et al. 1998), no effect on fruit SSC (Flores et al. 2004; Hartz et al. 2001) and improved yields (Hartz et al. 2005). Hartz et al. (2001, 2005) also found that K fertigation reduced the incidences of yellow shoulder and internal white tissue disorders in tomato but did not influence fruit SSC or juice color. Hartz (2001, 2005) attributed the absence of any response of fruit SSC to other overriding factors, such as cultivar and irrigation management, which potentially masked any K effects. Lin et al. (2004) found that supplemental K fertilization of melon in soil less culture increased fruit sucrose content but had no effect on fruit fructose and glucose concentrations. However, in the Lester et al. (2006) study, netted muskmelon fruit sucrose, glucose and fructose levels were increased by supplemental foliar K fertilization. It is worth noting that foliar Gly-complexed K treatments without surfactant had higher fruit fructose concentrations than the Gly-complexed K treatments with a silicone-based surfactant. A plausible explanation for this observation maybe silicone-based surfactant interference with the catalytic role of amino acids on invertase activity. Silicone-based reagents synthesize aminophosphonates (Boduszer and Soroka 2002) which act as antagonists of amino acids, inhibiting enzyme metabolism affecting the physiological activity of the cell (Kafarski and Lejcak 1991). Acid invertase (EC 3.2.1.26), found in melon fruits (Lester et al. 2001) is responsible for sucrose hydrolysis to fructose and glucose. Amino acids are catalysts in this hydrolysis reaction (Quick and Schaffer, 1996). It is likely the silicone-based surfactant interfered with the catalytic activity of the amino acid cofactor, thus down-regulating acid invertase allowing sucrose phosphate synthase (EC 2.3.1.14), the sucrose-synthesizing enzyme in melons (Lester et al. 2001), to remain active. Sucrose phosphate synthase specifically utilizes K as a cofactor to synthesize sucrose from glucose and fructose (Lester et al. 2001). The relative levels of sucrose and fructose in fruit also have important implications for consumer preference (relative sweetness) since fructose is perceived to be up to 80% sweeter than sucrose.

Total ascorbic acid and b-carotene were generally higher in fruits treated with K than in control fruits (Fig. 2). However, there were no consistent K source effects on these quality parameters. The beneficial effects of supplemental K probably resulted from a combination of improved leaf photosynthetic CO_2 assimilation, assimilate translocation from leaves to fruits, improved leaf and fruit water relations, increased enzyme activation and substrate availability for ascorbic acid and b-carotene biosynthesis all associated with adequate K nutrition (Hopkins 1963; Gross 1991). At present, it is unclear how high K concentrations in melon fruit increases ascorbic acid and beta-carotene concentrations, but increased synthesis through enzyme activation is a possible mechanism. In general, use of a surfactant increased fruit tissue concentrations of ascorbic acid and b-carotene (Fig. 2). However, the surfactant effect was not always consistent with both K forms; requiring further investigations into various surfactants applied with and without K foliarly to fruit-bearing plants. Use of specific foliar applied K forms, as a means to improve the antioxidant capacity (ascorbic acid and b-carotene, respectively) of melon fruits is a readily applicable, low-technology approach to improve the human wellness attributes of current commercially produced melon cultivars.

The beneficial effects of supplemental foliar K applications to fruit-bearing plants on melon fruit quality parameters were consistently positive regardless of growing season – spring or autumn. However, fruit produced in autumn had higher fruit firmness, ascorbic acid, b-carotene, total sugars and SSC (Fig. 2). Mechanisms for the improved quality parameters in autumn- compared to spring-grown fruit are still uncertain since average daily temperatures and cumulative heat units were slightly higher in autumn (~33°C and 728, respectively) than in spring (~28°C and 601, respectively). Cumulative photosynthetic photon flux during fruit development (from pollination to final harvest) was higher in spring (982 $mol \cdot m^{-2}$) than in autumn (637$mol \cdot m^{-2}$). New findings suggest that weather and climate play key roles in the human-health bioactive compounds in fruits (Lester

2006). These studies highlight how global climate change might affect the nutritional properties of food crop and how, through the use of foliar applied K, growers may counteract these effects.

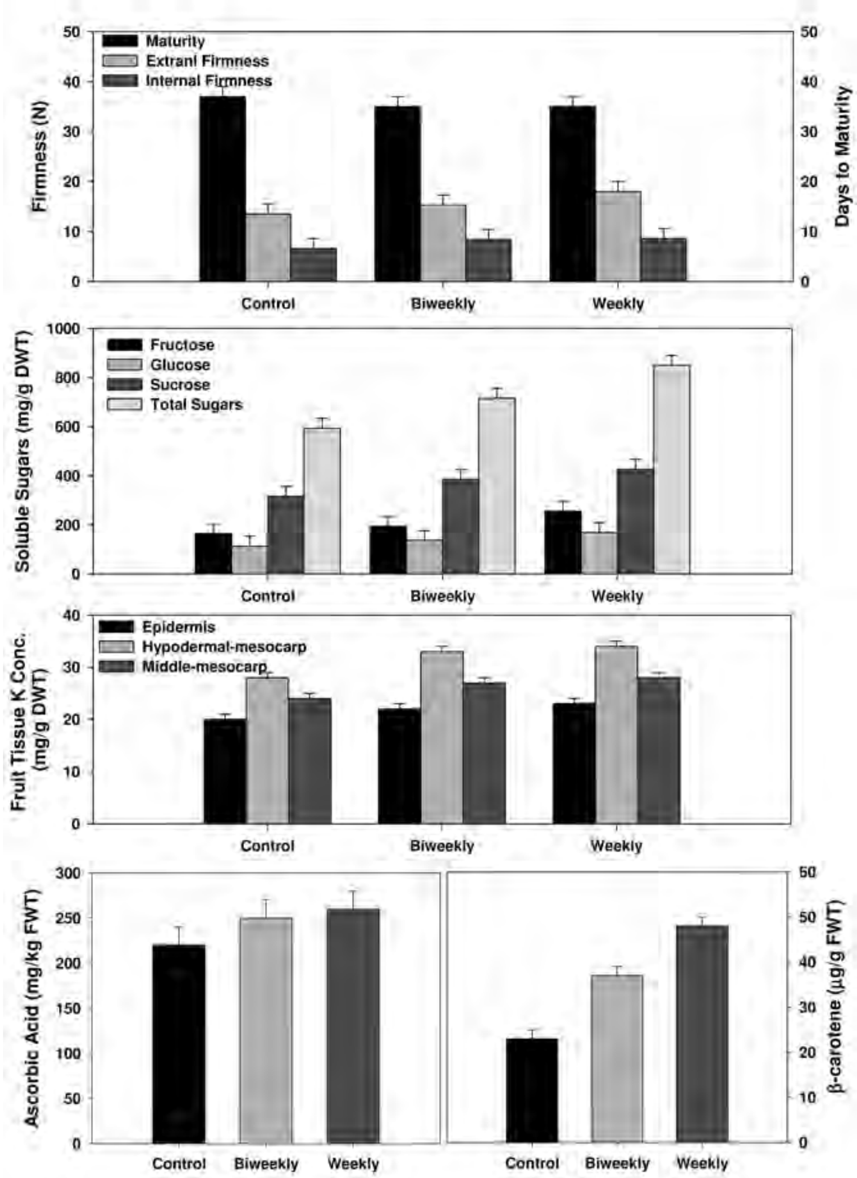
Number of foliar K applications

Supplemental foliar K applications resulted in earlier maturity of treated fruit compared to controls (Fig. 3). While this important marketability trait is not reported in K-treated fruit and the mechanisms for this effect are unclear, similar K-induced effects on fruit K concentrations and firmness have been reported (Chapagain and Wiesman 2004). Earlier maturity is a desirable economic trait in muskmelon production regions where adequate solar radiation flux can permit sufficient soluble solids accumulation in fruits before full-slip (abscission). Also, increased fruit firmness realized with weekly K foliar applications > biweekly applications > no foliar K application (Fig. 3), results in a melon fruit having an extended shelf-life which is another important marketability trait.

Fruit K contents resulting from the supplemental foliar application, increasing with weekly applications > biweekly applications of K compared to control fruit, was accompanied by increased fruit sugar levels (Fig. 3). Leaf photosynthesis rates are reported to increase with increased leaf K concentrations and this could be one mechanism of increased sugar contents in fruit (Terry and Ulrich 1973; Peoples and Koch 1979; Pettigrew 1999). However, leaf photosynthesis rates measured during the melon fruit maturation were similar among control and K-treated fruits (data not shown). Increased phloem loading, transport rate and/or unloading of sugars could also account for the increased fruit sugar levels, although it is uncertain whether this is a direct effect (enhanced phloem unloading in fruits) or an indirect effect (e.g. enhanced sucrose synthesis in source leaves) (Doman and Geiger 1979; Peel and Rogers 1982). Asche et al. (2001) provided evidence for faba bean (*Vicia faba* L.) indicating that K^+ channels are involved in sugar unloading. Potassium-induced increases in fruit sugar levels have also been reported in hydroponically grown muskmelon plants (Lin et al. 2004) however, the mechanism for this effect was also unclear. Although a threshold tissue K concentration for attaining optimum fruit sugar levels has not been established, our melon data (Lester et al. 2005 and 2006; Jifon and Lester 2009) provide additional evidence that fruit sugar concentrations can be increased through supplemental foliar K sprays.

Antioxidants ascorbic acid, derived from glucose (Hopkins 1963), and beta-carotene significantly increased with weekly K applications > biweekly applications > no foliar K application (Fig 3). Of the two antioxidants, beta-carotene dramatically responded to K foliar fertilizations increasing 70% and 100% with biweekly and weekly applications respectively. A benefit to the plant for having heightened levels of antioxidants is improved plant tolerance to various

Fig. 3 Effect of number of foliar applications of K (gylcine amino acid potassium) applied to glasshouse-grown, fruit-bearing muskmelon plants during fruit development on various marketability and quality attributes of fruit. All plants had sufficient soil fertilization. Data are means $\pm$ SD and are separated by the LSMEANS procedure of SAS (Statistical Analysis System, Cary, NC, USA) at $P \leq 0.05$ (Lester et al. 2005)



environmental stresses such as drought, low temperature, salinity, and sun burning all of which trigger cellular oxidative stress (Hodges et al. 2001; Cakmak 2005). The mechanism for K-induced oxidative stress tolerance is through increased ascorbic acid and beta carotene antioxidant activity. Ascorbic acid acts as an antioxidant by donating electrons and hydrogen ions thus reducing reactive oxygen species or free radicals. And beta-carotene is an accessory pigment in green tissues involved in photon capture protecting chlorophyll molecules from photo-oxidation due to excessive light thus reducing bleaching and sun burning and exhibits good radical-trapping antioxidant behavior under low (2%) oxygen conditions in fruit and root/tuber tissues (Gross 1991).

In melon fruit, the enzyme lipoxygenase (EC 1.13.11.12) has been associated with cellular membrane breakdown and fruit senescence through enhanced production of free radicals, however, this effect is minimized in fruit with high beta-carotene concentrations (Lester 1990). Ascorbic acid and beta-carotene also play similar important roles as antioxidants in humans when consumed in diets. Enhancing their accumulation in fruits, through carefully-timed, controlled K foliar fertilization to fruit-bearing plants will enhance the human wellness potential of melons (Lester and Eischen 1996; Larson 1997).

Conclusions

Supplementing soil K supply with foliar K applications to fruit-bearing plants improves fruit quality by increasing firmness, sugar content, ascorbic acid and beta-carotene levels. Among the K salts, KNO_3 has little or no beneficial effects on fruit quality when applied during fruit maturation, perhaps due to a dilution effect resulting from N stimulation of vegetative growth at the expense of roots and fruits. Perhaps foliar fertilization KNO_3 would be more beneficial during the vegetative growth stages when N is most needed for development of leaves with high photosynthetic capacity. The fruit quality improvements summarized in this review were obtained by implementing a simple low cost management tool that growers can easily adopt; resulting in nutritionally enrich fruits which, at little or no extra retail cost, benefits the consumer. Future research is needed to validate these findings in commercial field trials under different production environments (temperate vs. tropical) and productions systems (conventional vs. organic), and evaluate the effect of different K forms (glycine amino acid complexed K versus potassium chloride and others) on marketable quality and health-bioactive compound quality attributes of various fruits.

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Effect of potassium on fruit quality and their storage life

SK Mitra • SS Dhaliwal

Abstract Potassium has been described as the quality element and it plays a pivotal role in ensuring optimum quality of agricultural produce. Potassium has two main functions in the plant. Firstly it has an irreplaceable role in the activation of enzymes that are fundamental to metabolic processes especially the production of proteins and sugars. Only small amounts of K are required for this biochemical function. Secondly, K maintains the water content and thus helps in maintaining the turgor of cells as a biophysical role. Turgid cells maintain the leaf's vigour so that photosynthesis proceeds efficiently. The relationship between water and nutrient content of the cell controls the movement of both, through the plant and the transport of sugars produced by photosynthesis to storage organs of fruit. Potassium is required in much higher quantities for its physiological functions than for its biochemical role in plants. Fertilization with K is the first step to achieve the required quality standards. A great deal of research has established the beneficial effects of balanced nutrient supply, including adequate K, on the quality of the harvested produce. This is especially true for nutritional properties such as the protein content, oil, and vitamins and other functional aspects. Crops with an adequate supply of K have more weight, better appearance, taste and flavor, and also produce disease and pest free food. Numerous on-farm trials within IPI projects have proved that balanced fertilization with K helps the farmer to produce food, which fulfills the different quality criteria. Potassium improves the product's appearance and reduces the risk of rejection when the produce is offered for sale in the buyer's market.

Keywords Fruit quality • processing quality • storage life of fruits • mineral and vitamins

Introduction

Fruits are the health capsules being the main source of vitamins and minerals

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besides providing other dietary elements like carbohydrates, proteins, fiber, fats, vitamins and enzymes. India is endowed with favorable tropical, sub-tropical and temperate climate which is very conducive for producing high quality fruits round the year (Perrenoud 1990; Shamshiri and Usha 2004) in which more than 50 kinds of fruits are grown and important of them being Banana, citrus, grapes, mango, papaya, pineapple, passion fruits and litchi etc (Tandon and Kemmler 1986). Although the country has achieved fairly good production level of fruits to the tune of 43 million tones, but it is hardly sufficient to meet the 92 million tones, the total requirement of the country (Kumar et al. 2006). This warrants increase in production and productivity of fruit crops.

Judicious use of nutrients (N, P_2O_5 and K_2O) and their management is often regarded as one of the important aspects to increase the productivity of horticultural crops particularly fruit crops (Hardter and Krauss 1999; Hochmuth et al. 1994; Kafkafi et al. 2001). The only way to increase fruit production is to increase crop efficiency i.e. fruit yield per unit land area and cropping efficiency i.e. fruit yield and returns per unit of time. Efficient and rationale use of the fertilizers is imperative not only for obtaining more yields per unit area on a sustainable basis, but also to conserve the energy. The quantum jump in fruit production has to come from increase in productivity by intensive cultivation of fruit crops (Marshner 1995; Marshner et al. 1996). Apart from the fruit production, fruit quality is another aspect that has gained relative importance in modern day horticulture.

Even though K is abundant in many soils, the bulk of soil K is unavailable to plants, because the plant-available K pool is much smaller compared to the other forms of K in the soil. Potassium exists in several forms in the soil such as mineral K (90–98% of total), non-exchangeable K, exchangeable K, and dissolved or solution K (K^+ ions), and plants can only directly take up solution K (Lester et al. 2010). Uptake in turn depends on numerous plant and environmental factors (Usherwood 1985), which may limit K supply during the development stages, hence adversely affecting the quality attributes. For instance, adequate soil moisture supply is necessary to facilitate diffusion of K (which usually accounts for >75% of K movement) to plant roots for uptake. Mass flow, which also accounts for some soil K transport, also requires sufficient water in the soil. Marschner et al. (1996) found that increasing soil moisture from 10 to 28 percent doubled total soil K transport. Therefore, soil moisture deficits can limit soil K transport as well as uptake by the plants, thereby causing K deficiency.

The availability of K in the soil is strongly influenced by soil properties like pH, EC, OC, alkalinity, salinity, texture and CEC. For instance, clay soils typically have high K-fixing capacities and often show little response to soil-applied K fertilizers because much of the available K quickly adsorbs to clays (Sullivan et al. 1974). Such K fixation can help in reducing the leaching losses and can be

beneficial in the long-term as storage reservoirs of K for subsequent crops. Sandy soils, on the other hand tend to have a low K supplying power because of their low cation exchange capacities. In calcareous soils, Ca^{2+} ions tend to exist in high concentrations and dominate clay surfaces, and limit K sorption. High concentrations of cationic nutrients (particularly Ca^{2+} and Mg^{2+}) tend to limit K uptake by competing for binding sites on root surfaces. Consequently, crops grown on highly calcareous soils can show K-deficiency symptoms even though the soil test may report sufficient K (Kafkafi et al. 2001).

Potassium uptake also depends on plant factors, including genetics and developmental stage (vegetative and reproductive stages) (Marschner et al. 1996). Deficiency symptoms of K have been reported in many fruit crops. Management of K in light and porous soils with less organic matter is very important. In such cases application of heavy doses of organic matter will facilitate the retention of K by soil. Application of organic manures exclusively to meet the demand of the entire nutrient requirement of the crop or judicious and conjunctive use of both organic and inorganic is the option available to supply nutrients to fruit crops.

In many fruiting plant species, uptake of K occurs mainly during vegetative stages, when ample carbohydrate supply is available for root growth and uptake processes. Competition for photoassimilates between developing fruits and vegetative organs during reproductive growth stages can limit root growth and K uptake. Under such conditions, increasing soil K fertilization may not be enough to alleviate this developmentally-induced deficiency partly because of reduced root growth/activity during reproductive development and also because of competition from other cations for binding sites on roots (Marschner 1995).

Special attention needs to be given to the effectiveness of various K fertilizer sources and soil and foliar application of K on fruit quality. With the introduction of high yielding varieties and hybrids of fruits, responses to higher doses of fertilizer application have increased (Shamshiri and Usha 2004). Plant nutrients like N, P_2O_5 and K_2O available at high concentrations are often lost due to leaching, erosion, and volatilization due to limited time of absorption at different growth stages and the capacity of the soil to retain and release the applied nutrients (Tiwari et al. 1999). Among different nutrient sources in the soil, water-soluble sources of nutrients are in increased demand for fertigation (Sullivan et al. 1974; Tandon and Kemmler 1986).

Fruit crops are heavy feeders of potassium (K) and remove K higher than that of nitrogen (N) and phosphorus (P_2O_5) (Table1). Potassium, along with other macronutrients like N and P is an essential nutrient which is taken up by the crops in relatively high amounts compared to other nutrients (Gene et al. 2010; Haldter and Krauss 1999; Shawky et al. 2004). Potassium increases both yield as well as quality of fruit crops. Apart from it, potassium enhances the ability of fruit crops

Table 1 Nitrogen, phosphorus and potassium removal by fruit crops

Crop	Yield (t ha^{-1})	Nutrient removal (kg ha^{-1}) by fruit crops		
		N	P_2O_5	K_2O
Banana	40	250	60	1000
Citrus	30	270	60	350
Grapes	20	170	60	220
Mango	15	100	25	110
Papaya	50	90	25	130
Pineapple	50	185	55	350
Passion fruit	15	60	15	75

to withstand adverse conditions, helps in the development of a strong and healthy root system and increases the absorption and utilization of other nutrients (Sulladmath et al. 1984). To get optimum yield, different fruit plants differ in their nutrient (N, P_2O_5 and K_2O) requirement. For example, the available information on nutrients requirement of lemon to improve its yield and fruit quality is small as compared to oranges, however the Study of Koo (1963) showed that potassium requirement for lemon was much higher than that of orange and recommended rates of potassium fertilizers were 25 per cent higher than those for nitrogen, for optimum yield of lemon. The data presented in Table 1 showed that N, P_2O_5 and K_2O requirement of banana fruit was much higher than that of papaya and passion fruits. Drastically higher consumption of potassium (K_2O) was reported in case of banana fruit (1000 kg ha^{-1}). Citrus fruits also consume relatively higher amount of K_2O than that of grapes, mango and papaya fruits. Interestingly, citrus and pineapple need same amount of K_2O fertilizer with a yield difference of 20 t ha^{-1}.

Fruit quality is the degree of excellence or superiority is a combination of attributes, properties, or characteristics that give each commodity value in terms of its intended use (Geraldson 1985; Ramesh Kumar 2004). The relative importance given to a specific quality attribute varies in accordance with the commodity concerned and with the individual producer, consumer, and handler or market concerned with quality assessment. To producers, high yields, good appearance, ease of harvest, and the ability to withstand long-distance shipping to markets are important quality attributes (Koch and Mengal 1974; Mengal 1997). Appearance, firmness, and shelf-life are important from the point of view of wholesale and retail marketers. Consumers, on the other hand, judge the quality of fresh fruits on the basis of appearance at the time of initial purchase (Shamshiri and Usha 2004; Sipiora et al. 2005). Subsequent purchases depend upon the consumer's satisfaction in terms of flavor and quality of the edible part of fruits.

Potassium and physiological processes in fruit crops

In general, in addition to activation of more than 60 enzyme systems in fruits, K helps in photosynthesis, favors high energy status, maintains cell turgour, regulates opening of leaf stomata, promotes water uptake, regulates nutrients translocation in plant, favors carbohydrate transport, enhances N uptake, helps in protein synthesis and promotes starch synthesis.

Parameters to define fruit quality

Following are the important quality parameters in fruits which affect the economics of fruit production and nutrition value of fruits

Appearance quality factors

This parameter is very important from the marketing point of view to fetch higher price. It includes size, shape, color, gloss, and freedom from defects and decay. Defects can originate before harvest as a result of damage by insects, diseases, birds, hail, chemical injuries and various blemishes. Post-harvest defects may be morphological, physical, physiological, or pathological.

Textural quality factors

These include firmness, crispness, juiciness, mealiness, and toughness, depending on the commodity. Textural quality of horticultural crops is not only important for their eating and cooking quality but also for their shipping ability. Soft fruits cannot be shipped over long distances without substantial losses due to physical injuries. In many cases, the shipment of soft fruits necessitates that they be harvested at less than ideal maturity, from the flavor quality standpoint.

Flavour quality factors

These include sweetness, sourness (acidity), astringency, bitterness, aroma, and off-flavors. Flavor quality involves perception of the tastes and aromas of many compounds. An objective analytical determination of critical components must be coupled with subjective evaluations by a taste panel to yield useful and meaningful information about the flavor quality of fresh fruits and vegetables. This approach can be used to define a minimum level of acceptability. In order to assess consumer preference for the flavor of a given commodity, large-scale testing by a representative sample of consumers is required.

Nutritional quality factors

Nutritional quality factor includes fat, oil, arytenoids, flavonoids, sterols and antioxidants. Fresh fruits play a significant role in human nutrition, especially as sources of vitamins (Vitamin C, Vitamin A, Vitamin B, thiamine, niacin), minerals, and dietary fibre. Other constituents of fresh fruits that may lower the risk of cancer and other diseases include carotenoid, flavonoids, isoflavones, phytosterols, and other phytochemicals (phytonutrients).

Potassium and nutritional value of crops

The nutritional value of fruits refers to the content of certain constituents such as protein, oil or fat, starch, mineral components and vitamins. The contents of fiber as well as the energy content are widely used parameters in assessing the value of food stuff in the human diet (Tandon and Kemmler 1986). Potassium (K) has a significant influence on increasing many human-health related quality compounds in fruits (Usherwood 1985). The content of nutritive elements, like proteins or oils, is used in many countries as a basis for procurement systems and thus, is an economic factor. Studies with the N isotope N_{15} showed that plants well supplied with K were able to take up more N, and moreover convert the N more rapidly into protein. Nitrate in the plant is reduced first to amines and then incorporated into amino acids to ultimately form proteins. A small K supply restricts NO_3 transport and inhibits protein formation, leading to an accumulation of nitrate-N and soluble amino-N in the plant. K influences on quality can also be indirect as a result of its positive interaction with other nutrients (especially with nitrogen) and production practices (Usherwood 1985). Potassium also improves and citric and ascorbic acid (vitamin C) content in juice, while influences other juice characteristics, like the acid/sugar ratio and soluble solids content (Koo 1985). The effect of K on increasing vitamin C is related with the improved sugar metabolism in the plant under proper K nutrition (Mengel 1997)

Potassium and food appearance

An adequate supply of K promotes the formation of fruits through a more intensive and longer period of photosynthesis. In citrus, K nutrition positively influences the size of fruit, thickness of the rind and fruit color (Anonymous 1975; Lester et al. 2010). The improved yield is due, in part, to reduced fruit fall from the tree and larger fruit size. Physiological disorders of citrus fruits like plugging and creasing, are associated with high N and low K availability. Potassium deficiency resulting in small, thin-skinned fruit promotes fruit splitting, even though extra K will not always correct normal splitting in susceptible cultivars. Plants adequately supplied with K show fewer incidences of pests and diseases (Shamshiri and Usha 2004). Fissures, cracks and lesions observed on K deficient fruits and leaves not only offer easy access to invading pathogens but also are less appealing to potential consumers at the market.

Contribution of various workers in generation of information on quality parameters in different fruits is summarized in Table 2. Fruit size and peel colour are important fruit characteristics for fresh market, while for their processing, soluble solids, juice, pectin and essential oil content are important parameters which help during storage.

Table 2 Information available on quality parameters of fruits

Quality Parameter	Fruit	References
Fruit size	Citrus	Shamshiri and Usha 2004
	Grape	Wojcik 2005
	Banana	Kumar and Kumar 2007
	Litchi	Mitra 2009
	Mango	Wojcik 2005
	Guava	Zehler et al. 1981
Colour	Citrus	Shawky et al. 2004
	Grape	Usherwood 1985
	Apple	Tandon and Kemmler 1986
	Litchi	Tandon and Kemmler 1986
	Banana	Kumar and Kumar 2007
Soluble solids	Citrus	Tiwari et al. 1999
	Banana	Kumar and Kumar 2007
	Grape	Usherwood 1985
	Guava	Mitra 2009
	Mango	Wojcik 2005
	Papaya	Sulladhmath et al. 1984
	Pineapple	Stewart 1956
Acidity	Citrus	Shawky et al. 2004
	Grape	Usherwood 1985
	Papaya	Sulladhmath et al. 1984
	Guava	Zehler et al. 1981
	Mango	Wojcik 2005
	Pineapple	Stewart 1956
	Banana	Kumar et al. 2006
Soluble solids	Citrus	Shawky et al. 2004
	Guava	Zehler et al. 1981
	Aonla	Wojcik 2005
	Banana	Kumar and Kumar 2007
	Pineapple	Stewart 1956
	Papaya	Sulladhmath et al. 1984

Effect of foliar application of potassium on yield and quality of fruit crops

There are several potassium chemicals that can be used commercially in fruit orchards. Potassium nitrate and potassium sulphate can be applied as foliar sprays to increase the fruit yield and quality. The double salt sulphate of potash magnesia is widely used in areas where magnesium deficiency occurs. Using ammonium fertilizers as the nitrogen source can increase the uptake of K. An optimum level of K is most important in relation to external aspects of fruit quality (Embleton et al. 1973). Excessively high K levels result in large fruits with coarse, thick peel and poor colour. Moreover, early and intensive regreening will occur in such fruit plants (orchards). On the other hand too low K levels in fruit plants result in small fruits, which are rejected by the fresh fruit and export markets, in spite of their thin rinds and good colour. Potassium decreases the loss of fruit from creasing, splitting and the addition of auxins can further reduce these peel disorders. In citrus, K improved both the citric and ascorbic acid content of the juice, as well as other juice characteristics, like the acid/sugar ratio and soluble solids content. Vitamin C (commonly referred to as ascorbic acid) is perhaps the most popular vitamin.

Soil and foliar application of K has been shown to increase the level of ascorbic acid in banana, guava and papaya. Fruits crops receiving adequate K give a larger root yield with increased sugar content and consequently much larger sugar content in the fruits. The lower sugar content in fruits receiving inadequate K derives from reduced translocation of assimilates from the leaves into the storage organ due to restricted phloem loading.

Table 3 Effect of potassium fertilization on leaf K, yield and fruit size of 'Shamouti' orange

Treatment	1984	1985	1986	1987
Leaf K% (D. Wt.)				
-K	0.45	0.60	0.44	0.51
+K	0.64	0.85	0.67	0.87
Sign.	+	+	+	+
Yield (ton ha^{-1})				
-K	67	57	71	67
+K	77	54	86	72
Sign.	+	-	+	-
Fruit weight (g)				
-K	181	211	187	172
+K	193	256	197	222
Sign.	-	+	-	+

Source : Dasberg 1988, + Significant, - Not significant

The data presented in Table 3 depicted the effect of potassium fertilization on leaf K content, fruit yield and fruit size of Shamouti a variety of orange over a period of 4 years beginning from 1984 to 1987. From 1984 till 1987 a significant and positive increase in % leaf K concentration (on dry wt. basis) was observed with the application of K as compared to the control whereas fruit yield (t ha^{-1}) and fruit weight (g) showed a positive and significant increase with K application on alternate years. Potassium application increased the orange yield significantly in 1984 and 1986 as compared to control, whereas fruit weight was significantly higher in 1985 and 1987.

Fruit weight (kg), TSS (%), acidity (%) and ascorbic acid (mg 100 g^{-1} pulp) content increased with an increase in concentration of KCl and highest values for these were observed at foliar application of 2.0 percent KCl concentration as compared to control and 1.0 percent KCl concentration (Table 4). Fruit weight was significantly higher at 2.0 percent KCl concentration by 8.8 kg as compared to control whereas TSS (%) was significantly lower in control as compared to 1.0 percent and 2.0 percent KCl concentrations by 0.24 and 0.38 percent respectively. Similarly, acidity (%) was significantly higher in 1.0 percent and 2.0 percent KCl concentrations as compared to control by 0.042 and 0.030 percent respectively whereas a significant difference of 0.012 percent was also observed between 1.0 percent and 2.0 percent KCl concentrations. Ascorbic acid content at 2.0 percent KCl concentration was significantly greater than that for control and 1.0 percent KCl concentration by 4.7 and 2.5 mg 100 g^{-1} pulp respectively. Application of foliar K markedly improved several cantaloupe fruit quality parameters, despite sufficient soil test K levels (Koch and Mengal 1974; Usherwood 1985).

Table 4 Effect of foliar application of KCl on fruit weight and quality of Sardar guava

Treatments	Fruit Weight (kg)	TSS (%)	Acidity (%)	Ascorbic Acid (mg 100 g^{-1} pulp)
Control	133.0	11.28	0.296	237.7
1.0% KCl *	136.7	11.52	0.326	239.9
2.0% KCl	141.8	11.66	0.338	242.4
CD (P=0.05)	5.61	0.144	0.009	1.543

Source: Kundu et al. 2007; *Two sprays - May 10th and September 10th.

The experiments conducted at Bidhan Chandra Krishi Vishwavidyalya, Mohanpur, West Bengal indicated that increase in levels of applied K increased the yield of fruits varying from 13.8 to 35.7 percent in different fruits (Table 5). Similarly, the total sugar yield increased from 4.2 to 34.1 percent in different fruits.

Table 5 Effect of K application on yield and total sugar in different fruits

Fruit	Variety	Increase in applied K (g $plant^{-1}$ yr^{-1})	Increase in fruit Weight (g)	Per cent Increase	Increase in total Sugar (%)	Per cent increase
Mango	Fazli	150 to 1000	595 -748	25.7	12.0-12.5	4.2
Banana	Giant	120 to 240	117-139	18.8	14.6-16.7	14.4
Pine Apple	Kew	200 to 600 **	1400-1900	35.7	12.8-15.2	18.7
Litchi	Bombai	200 to 600	18.1-20.6	13.8	13.9-15.8	13.7
Guava	Sardar	130 to 260	152-176	15.8	7.93-8.72	14.3
Papaya	Ranchi	200 to 600**	1420-1640	15.3	5.07-6.80	34.1
Mandarin orange	-	200 to 600	84-107	27.4	8.30-9.80	18.1

Source: Mitra 2009 ** kg ha^{-1}

The maximum increase in fruit weight (35.7 %) was observed in pine apple (Kew var.) when the rate of K application was increased from 200 to 600 kg ha^{-1} yr^{-1}. Correspondingly, an increase of 18.7 percent in total sugar was also observed for the same fruit. The highest increase in fruit size of pine apple was followed by Mandarin orange where an increase of 27.4 percent was observed when the rate of K application was increased from 200 to 600 g $plant^{-1}$ yr^{-1} with a corresponding increase of 18.1 percent in total sugars. In mango (var. Fazli) when the rate of K application was increased from 150 to 1000 g $plant^{-1}$ yr^{-1} there was a corresponding increase of 25.7 percent and 4.2 percent in fruit weight and total sugars respectively. An increase of 18.8 and 14.4 percent respectively, was observed for fruit weight and total sugar in banana (Giant var.) for a 120 g increase in K per plant when the rate of K application was increased from 120 to 240 g $plant^{-1}$ yr^{-1}. Fruit weight in guava (Sardar var.) increased by 15.8 percent, while a corresponding increase of 14.3 percent was also observed for the total sugar when the rate of K application was increased from 130 to 260 g $plant^{-1}$ yr^{-1}. In Papaya, with an increase of about 400 g K $plant^{-1}$ yr^{-1} there was an increase of 15.3 and 34.1 percent in fruit weight and total sugar respectively. Lowest increase in fruit weight (13.8%) with a corresponding increase of 13.7 percent in total sugars was observed in Litchi (Bombai var.) although the rate of K application was increased from 200 to 600 g $plant^{-1}$ yr^{-1}.

The effect of sulphate of potash (SOP) on yield, quality and post-harvest life of eypoovan banana has been observed (Table 6). Increased concentrations of potassium sulphate improved the bunch weight, TSS, sugar to acid ratio and self-life of banana. With an application of 1.5 percent in SOP, bunch weight increased significantly by 4.47 kg as compared to control treatment. Significant increases of 1.1 and 1.64 kg respectively in bunch weights were observed as the SOP concentration was gradually increased by 0.5 percent upto 1.5 percent. On the other hand, TSS (%) at SOP concentrations of 1.0 and 1.5 percent was similar but significantly higher than control by 4.5 percent. A decrease in acidity (%) was

Table 6 Sulphate of potash (SOP) foliar spray effects on yield, quality and post-harvest life of eypoovan banana

Treatments	Bunch weight (kg)	TSS (5)	Acidity (%)	Sugar:Acid ratio	Shelf life (Days)
Control	10.80	24.4	0.40	50.9	6.5
0.5% SOP *	11.53	27.9	0.30	71.8	7.8
1.0% SOP	12.63	28.9	0.23	84.3	7.8
1,5% SOP	14.27	28.9	0.23	97.6	8.7
CD (P=0.05)	1.02	2.06	0.024	6.72	0.98

Source: Kumar and Kumar 2007; * Sprayed twice, initially after the opening of last hand (7th month after planting) and 30 days later

observed in eypoovan banana with an increase in SOP concentration and acidity at 1.0 and 1.5 percent concentrations of SOP was significantly lower than control by 0.17 percent. A rapid increase in sugar to acid ratio (sugar:acid) with increasing SOP concentration was observed with highest ratio being observed at 1.5 percent SOP concentration which was significantly higher than control by 46.7 whereas it was significantly higher at 0.5 and 1.0 percent SOP concentrations by 20.9 and 33.4 respectively as compared to control. Shelf life (days) was similar for 0.5 and 1.0 percent SOP concentrations (7.8 days) but it was significantly higher than for control by 1.3 days. Similarly, shelf life was more at 1.5 percent SOP concentration as compared to control by 2.2 days.

In banana, potassium improves fruit weight and number of fruits per bunch, and increases the content of total soluble solids, sugars and starch (Table 7) (Bhargava et al. 1993).

Table 7 Effect of K levels on yield and quality of bananas

K_2O (g pl^{-1})	Bunch weight (kg)		Yield (t ha^{-1})		Total sugar (%)		TSS (%)		Acidity (%)	
	P	R	P	R	P	R	P	R	P	R
0	12.0	12.1	30.0	30.2	11.0	11.9	15.9	16.0	0.59	0.59
240	13.4	14.2	33.5	35.5	12.6	12.6	16.5	16.4	0.55	0.55
480	15.2	15.3	38.0	38.2	13.1	13.1	17.0	17.0	0.53	0.52

Source: Bhargava et al. 1993. P = Plant, R=Ratoon

Effect of Potassium on storage/shelf life of fruit crops

The effects of K on shelf life are predominantly favorable, both through slowing senescence and through a decrease of numerous physiological diseases. Potassium increases firmness and strengthens the skin of fruits, thus they are not damaged easily during transport, resist decay for a longer period and stay fresh longer.

Increased K application reduces the post harvest moisture loss by increasing the weight of the harvested organs and maintaining tissue integrity. Potassium also reduce the incidence of some storage fungal diseases that may cause considerable losses, because fruits, tubers or roots showing even minor damage must be discarded before marketing. Storage compounds accumulating in the harvested organ during growth and maturation are consumed in the course of metabolic activitites during storage. Respiration includes the oxidative breakdown of sugars, starch and organic acids into carbon dioxide and water, with the concurrent production of energy, heat and intermediary compounds to be used in biochemical reactions. With a shortage of K, the rate of respiration is increased and more energy is required for this function, thus fruits do not last long in storage.

The direct relationship between K and storage life of fruits has been reported by various workers (Table 8).

Table 8 Relation of K and storage life of fruits

Fruit	Effect	References
Mango	+	Wojcik 2005
Citrus	+	Shamshiri and Usha 2004
Pineapple	+	Stewart 1956
Grape	+	Wojcik 2005
Banana	+	Kumar et al. 2007

\+ Positive effect

Adequate K nutrition has been associated with increased shelf life, and shipping quality of many horticultural crops (Kumar et al. 2006). Fruits from trees sprayed with K were firmer and better quality than the control fruit during the storage period (Robertson et al. 1990). K application on Kaki fruit increased fruit firmness (El-Fatah et al. 2008) thus improving storage period. Potassium enhanced storage and shipping quality of bananas and many other crops, and also extends their shelf life (Bhargava et al. 1993; Geraldson 1985; Koo 1985; Mengel 1997; Usherwood 1985; Von Uexkll 1985). Quality of citrus fruits during storage is also influenced by K nutrition of the tree. The incidence of stem-end rot and green mold is reduced as K fertilization rate is increased, therefore fruit loss during transport is reduced and shelf life in the supermarket is increased (Koo 1985). A low potassium nutrition results in thin and fragile bunches with shorter shelf life (Von Uexkll 1985).

Stewart (1956) studied the post harvest behavior of pineapple as affected by different sources of potassium (Table 9) at harvest and at 28 days of storage and observed that at harvest maximum TSS (15.5%) was observed with KCl while the minimum value for TSS (15.1%) was observed when K_2SO_4 was used as a source of K. At 28 days of storage, TSS was highest (15.5%) when a mixture of KCl+

Table 9 Post-harvest behaviour of pineapple affected by sources of potassium

Source of K	TSS^o Brix	Acidity (%)	Firmness
At Harvest			
KCl	15.5	0.55	11.7
K_2SO_4	15.1	0.50	12.7
KCl+K_2SO_4	15.4	0.53	13.9
At 28 days of Storage			
KCl	14.7	0.67	8.5
K_2SO_4	15.4	0.54	9.6
KCl+K_2SO_4	15.5	0.59	8.0

Source: Stewart 1956

K_2SO_4 was used and lowest (14.7) when KCl was used as a source of K. Similar trends were observed for acidity at harvest as well as at 28 days of storage. At harvest, maximum acidity (0.55%) was observed with KCl while the minimum value for acidity (0.50%) was observed when K_2SO_4 was used as a source of K, at 28 days of harvest, highest (0.67%) and lowest (0.54%) values of acidity were observed when KCl and K_2SO_4 were used as sources of K respectively. At harvest, firmness was maximum (13.9) when a mixture of KCl+ K_2SO_4 was used and minimum (11.7) when KCl was used as a source of K while at 28 days of storage maximum (9.6) firmness was observed while using K_2SO_4 while minimum (8.0) was observed using a mixture of KCl+ K_2SO_4. Post-harvest characteristics of fruits were more affected by K rates than by K sources.

The scientific literature also contains examples of studies with conflicting results of the beneficial effects of K fertilization on fruit quality. These conflicting results can be explained by taking into consideration the differences in modes of fertilization i.e. soil applied (dry) vs. foliar application, fertigation or hydroponic applied, differences in forms of K fertilizer e.g. glycine-complexed K, versus K_2SO_4, KCl, or KNO_3 from K fertilization, timing of application with regard to crop phenology or soil chemical and physical properties such as pH, calcium and magnesium contents, and textures (sandy vs. clay). These properties are known to influence soil nutrient availability and plant uptake, and soil fertilizer K additions under such conditions may have little effect on uptake, yield and fruit quality (Mengal 1997). In a number of studies involving several fruiting crops e.g. mango and citrus where soil-applied fertilizer K was compared to foliar K applications, the latter approach consistently resulted in improved fruit quality attributes during processing whereas the former approach generally had little or no effects (Marshner et al. 1996; Perrenud 1990). Furthermore, in studies where several fertilizer K salts were evaluated, fruit quality improvements during storage appeared to depend on timing of application as well as fertilizer K formulation. For instance, when mid- to-late season soil or foliar K applications were made using KNO_3 there were little or no improvements in fruit quality or human nutritional quality attributes and in some instances, these attributes were actually inferior compared to fruit from control plots (Lester et al. 2010).

Conclusions

Potassium is important in optimizing both crop yield and economic quality of fruit crops. A balanced nutrition allows K to contribute its best towards higher yield, quality and profitability. Potassium enhances the quality parameters of fruits thus helping consumers to eat good quality and nutritious fruits and farmers to get more profit.

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

Roland J Buresh • Mirasol F Pampolino • Christian Witt

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

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

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

Introduction

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

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

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

(1990) was used to provide a generic empirical relationship between grain yield and nutrient accumulation in rice plants (Witt et al. 1999), which was subsequently combined with the estimation of attainable yield, nutrient balances, and probable yield gains from added nutrient to determine field-specific fertilizer requirements for rice (Witt and Dobermann 2004).

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

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

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

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

The objectives of this study are:

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

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

Materials and methods

Internal nutrient efficiencies for rice

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

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

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

[a]HI = harvest index

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

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

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

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

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

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

Determination of K and P balances

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

[a] n = number of observations
[b] SD = standard deviation

Determination of fertilizer K and P rates

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Results

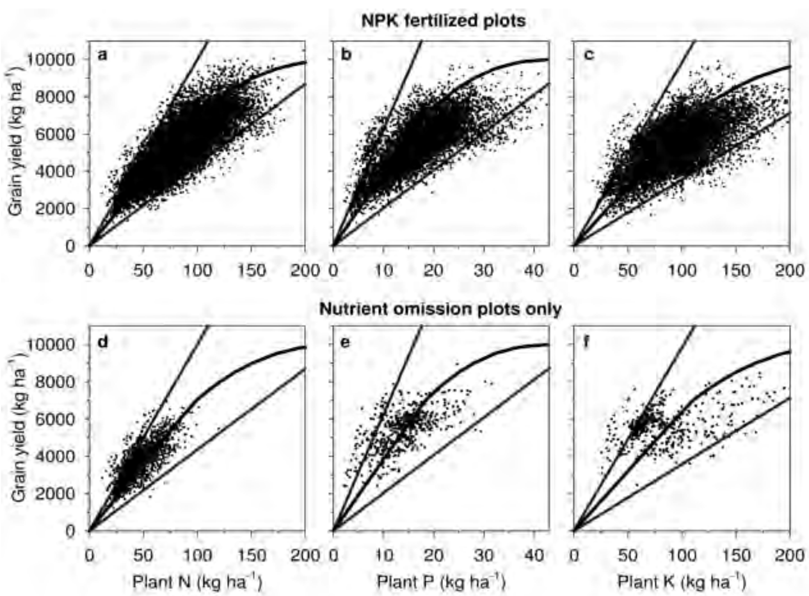
Internal nutrient efficiencies for rice

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

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

Observations from nutrient omission plots are shown for no added N in Fig. 1d, no added P in Fig. 1e, and no added K in Fig. 1f. In each case the presented boundary lines and QUEFTS model were derived using data from NPK fertilized plots (Table 3). In the absence of a nutrient, many observations concentrated near

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



the upper boundary line for IE, which generally reflects severe nutrient deficiency. High IE for a nutrient in plots where the nutrient is omitted (Fig. 1def) corresponds to markedly lower RIE for nutrient omission plots than for NPK fertilized plots (Table 2). For P and K about 5% of the total plot-level observations were from nutrient omission plots. In these cases, the inclusion of nutrient omission plots in the data set had no pronounced effect on the calculated RIE. For N, for which 14% of the total plot-level observations were from N omission plots, the inclusion of N omission plots in the data set reduced the calculated RIE by 3% (Table 2).

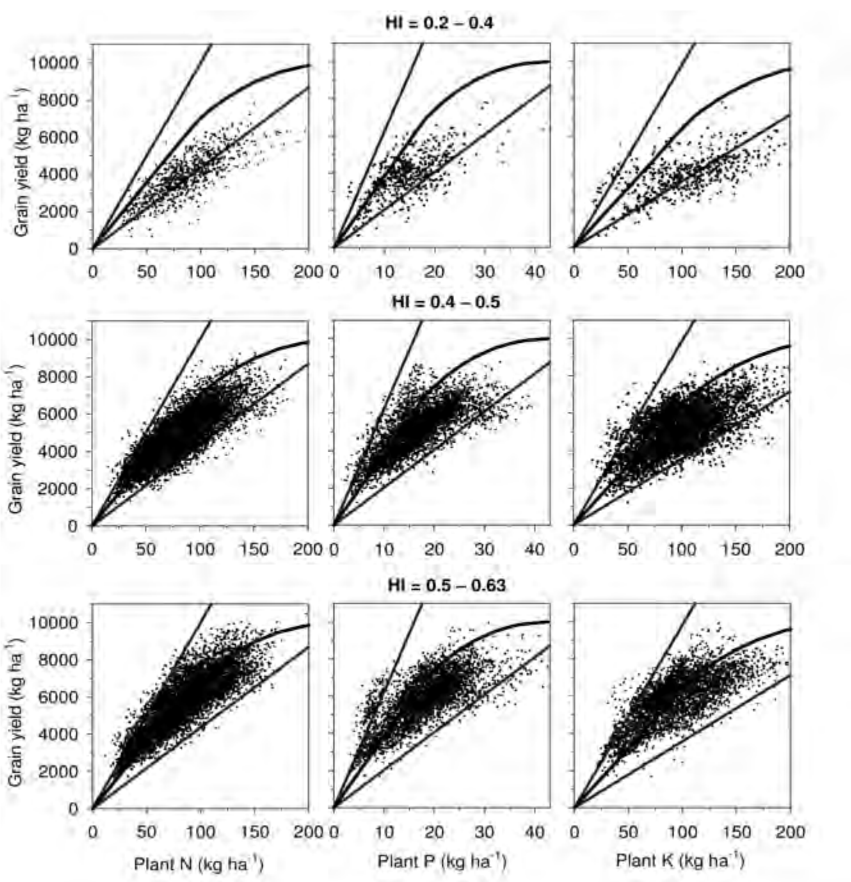
The IEs for N, P, and K were relatively low at low harvest indices (Fig. 2). At harvest index = 0.2 to 0.4, many observations for the relationship of grain yield and plant N, P, or K were concentrated near the lower boundary line determined with QUEFTS using data from NPK fertilizer plots with harvest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

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

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

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

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



exclude from analysis with QUEFTS the data from plots where plant growth was limited by factors other than nutrient supply. The strong influence of harvest index on RIE, especially for K and N, verifies the merit of excluding data with harvest index <0.4 when factors other than nutrients were likely limiting the

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

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

[a] n = number of observations
[b] SD = standard deviation

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

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

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

yield of semi-dwarf cultivars. The exclusion of data from omission plots slightly increased RIE obtained from the linear portion of the QUEFTS prediction. With the exclusion of omission plot data, the RIE for nutrients increased from 14.1 to 14.6 kg N per tonne of grain, 2.6 to 2.7 kg P per tonne of grain, and 15.6 to 15.9

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

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

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

Nutrient balances in rice-based cropping systems

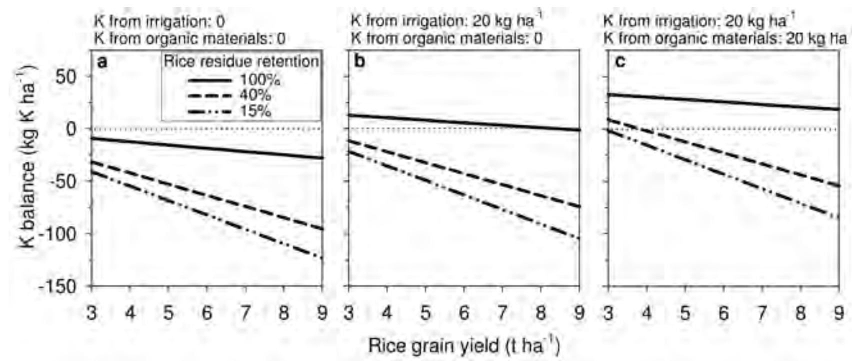
Continuous rice cropping

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

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

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

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

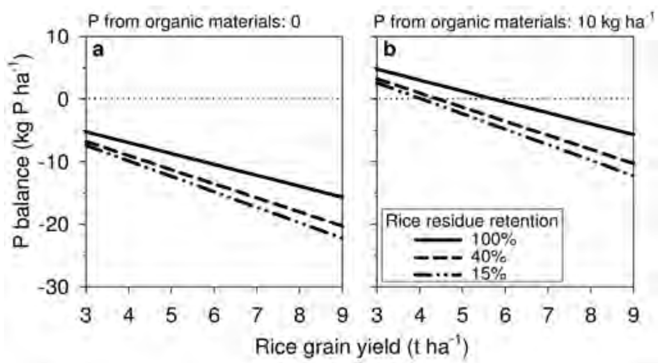


The K balances in Fig. 3 with 100% retention of crop residue represent fields with combine harvesting without subsequent removal of crop residue. They also represent fields with manual harvesting and complete return of crop residue to the field after threshing. The burning of rice residues, though increasingly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

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

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

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



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

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

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

[a] n = number of observations
[b] b SD = standard deviation
[c] Unpublished data from IRRI Reversing Trends in Declining Productivity project, 1997-2000

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

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

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

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

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

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

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

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

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

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

Rice–wheat system

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

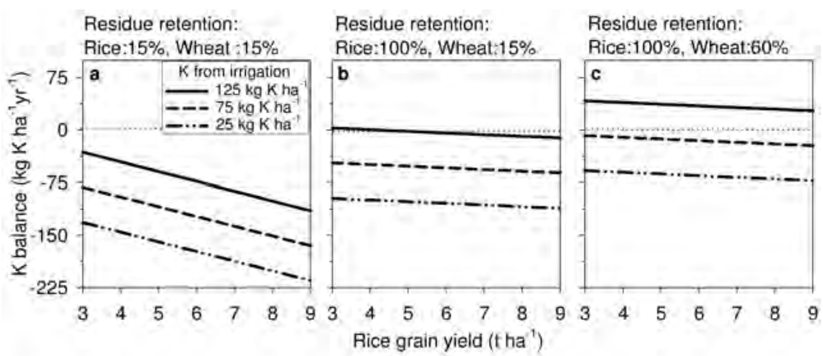
In Northwest India, within the northwestern part of the IGP, the groundwater used for irrigation of rice–wheat is relatively high in K. Reported K concentrations for 242 samples from tube wells in the central plain region of the state of Punjab in Northwest India ranged from 0.87 to 38.2 mg L^{-1} with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

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

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

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

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



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

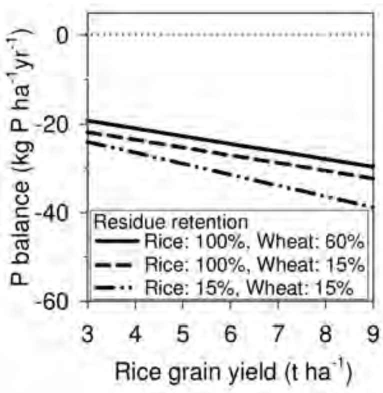
Wheat residue is often removed from the field for use as fodder in Northwest India, whereas rice residue is less valuable for fodder and is often partially or completely retained in the field (Mandal et al. 2004). The K balances in Fig. 5a with 15% retention of both rice and wheat residue represent removal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

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

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

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

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

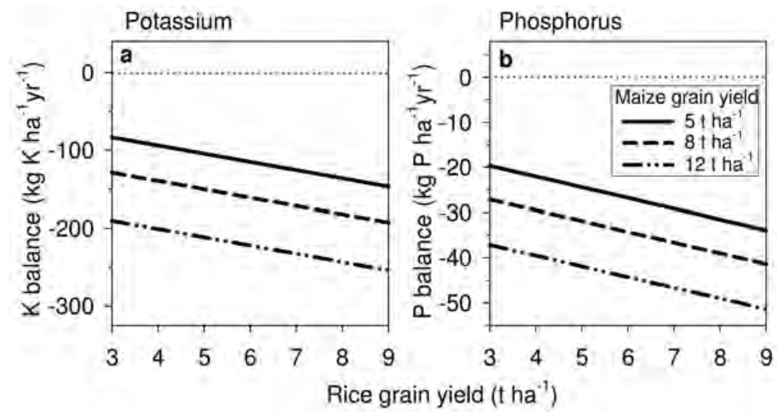


Rice–maize system

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

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

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

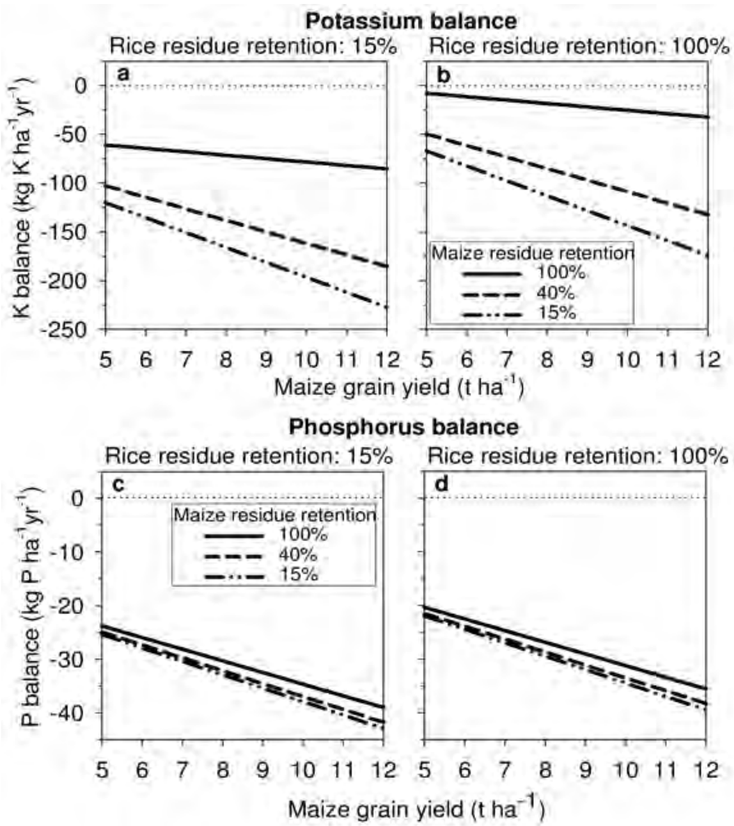


Nutrient balances for the rice–maize system are strongly affected by the yield of maize (Fig. 7). Hybrid maize in a rice–maize system can achieve a yield up to 12 t ha^{-1} with good management practices and a sufficient supply of nutrients in farmers' fields (IPNI, unpublished data), which is markedly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

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

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

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



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

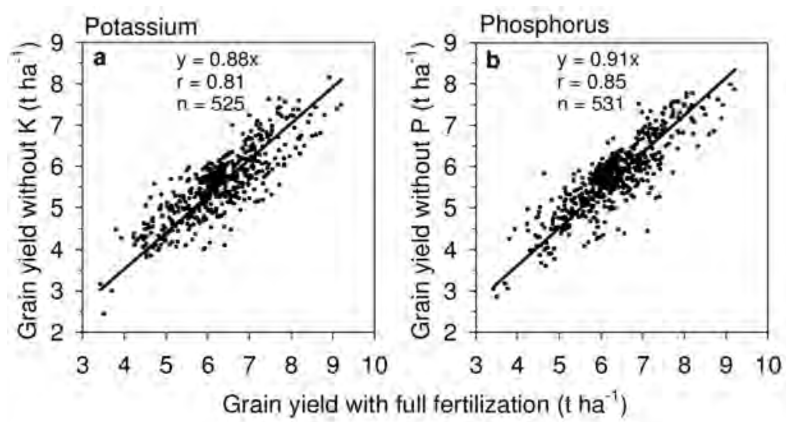
The P balances are affected more by maize yield than by management of maize and rice residues. The P deficits and hence likely need for fertilizer P increase in direct proportion to the yield of maize (Fig. 8cd).

Determination of fertilizer K and P rates

Yield gain approach

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

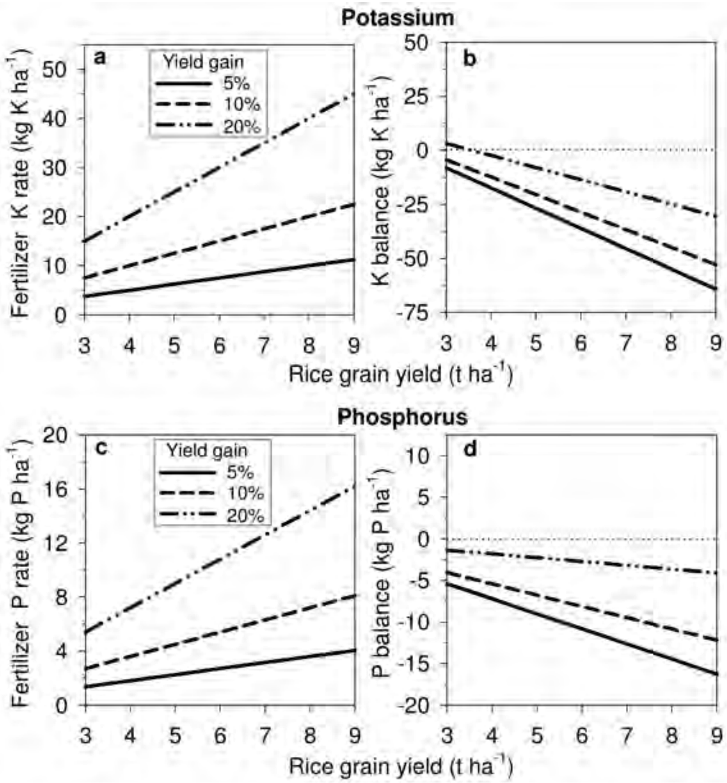
Fig. 9 Relationship between rice grain yields in a plot with full fertilization of ample N, P, and K and an adjacent plot without application of K or P but sufficient amounts of other nutrients to prevent their limitations. Data are from trials conducted in farmers' fields in Bangladesh, India, Indonesia,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



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

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

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



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

Fertilizer K and P requirements determined by the yield gain approach (equations 7 and 8) increased with increasing target yield (Fig. 10ac), but the K and P rates did not increase sufficiently fast to prevent increasing depletion of soil

fertility with increasing yield within the ranges of yield gain common for irrigated rice (Fig. 10bd). The same trends of increasing fertilizer rates and decreasing nutrient balances with increasing yield occur when lower recovery efficiencies (RE_K = 0.35 and RE_P = 0.22) corresponding to median values reported by Witt and Dobermann (2004) were used to determine fertilizer requirements (data not shown).

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

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

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

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

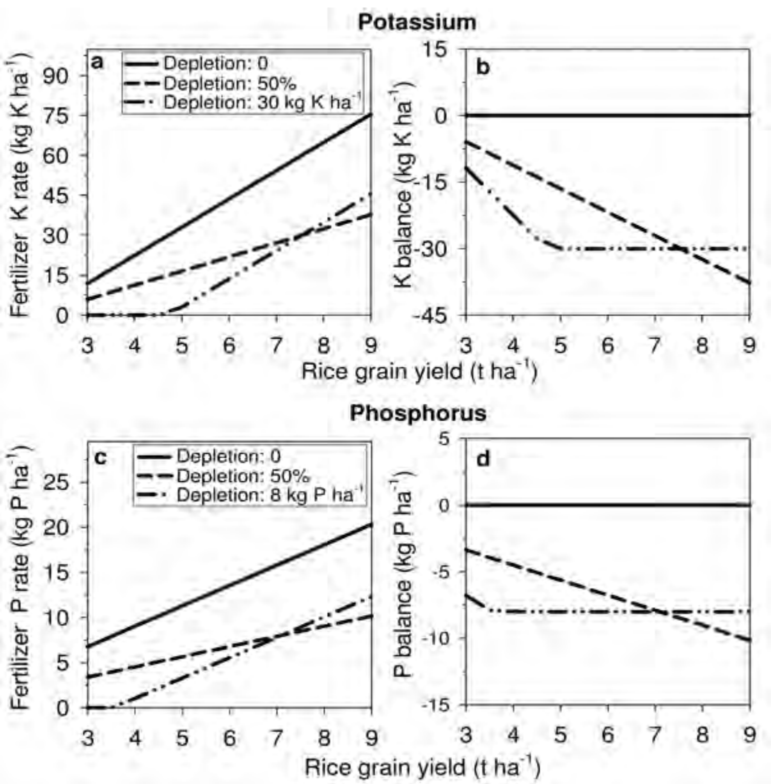
$$FP = (GY - GY_{0P}) \times 1000/AE_P \qquad [20]$$

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

Nutrient maintenance based on nutrient balance approach

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

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



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

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

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

Partial maintenance plus yield gain approach

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

In Fig. 12 the fertilizer K and P rates and balances for a partial maintenance approach with limited depletion (K_S = 30 kg K ha^{-1} and P_S = 8 kg P ha^{-1}) are compared alone (equations 13 and 14) and in combination with a yield gain approach (equations 17 and 18). Yield gain was either set at 20% of attainable yield ($GY - GY_0 = 0.2GY$) or at a constant 1 t ha^{-1} ($GY - GY_0 = 1$). In Fig. 13 the

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

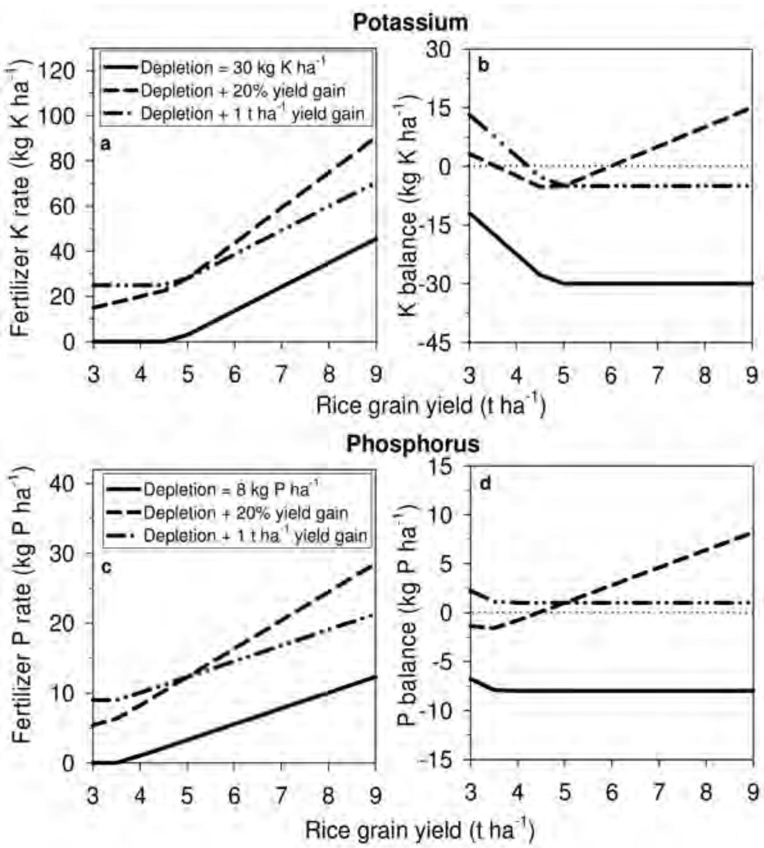
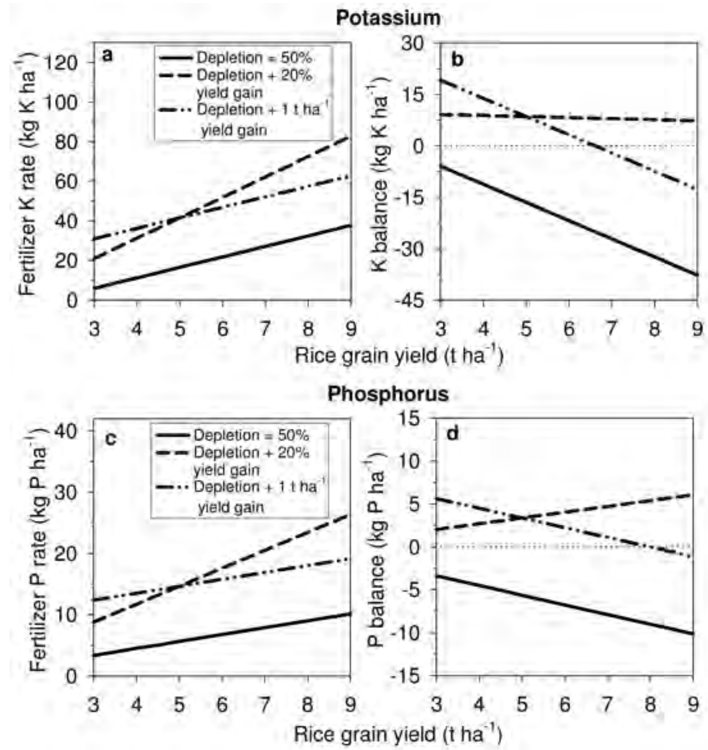


Fig. 13 Fertilizer K and P rates for rice determined with a partial maintenance + yield gain approach in which maintenance rates of K and P are a fraction of the nutrient depletion determined with nutrient balances. In each case 40% of rice residue was retained in the field, and K input from irrigation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



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

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

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

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

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

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

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

Equations 17 and 18 for the limited depletion option become:

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

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

Discussion

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

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

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

Internal nutrient efficiencies for rice

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

K requirements when fertilization is balanced to match crop needs.

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

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

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

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

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

Nutrient balances in rice-based cropping systems

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

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

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

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

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

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

Potassium deficiencies in the rice–wheat system are more likely in areas with little K input from irrigation water and limited retention of crop residues. Although K is high in irrigation water from tube wells in the northwestern IGP (Pasricha et al. 2001), irrigation water can be lower in K in other rice–wheat areas of the IGP. Analysis of 21 samples of irrigation water from tube wells in rice–wheat areas of Uttaranchal, India, for example, revealed relatively low K concentration ranging from 0.8 to 2.8 mg L^{-1}, with a median of 1.3 mg L^{-1}

(unpublished data, IRRI Reversing Trends in Declining Productivity project, 1997–2000). At these K concentrations, the K input from irrigation water for a rice–wheat cropping cycle would approximate 25 kg ha^{-1}, leading to markedly negative K balances regardless of residue retention (Fig. 5).

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

Determination of fertilizer K and P rates

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

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

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

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

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

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

approximate a fraction of the yield with full fertilization (Fig. 9).

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

Conclusions

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

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Site specific potassium management in rice based cropping systems in India

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

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

Introduction

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

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

Potassium scenario in India

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

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

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

Table 1 Nutrient uptake in important cropping systems

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

Source: Yadav et al. 1998

Table 2 An illustrative nutrient balance sheet of Indian Agriculture

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

[#] Gross balance is calculated on the basis of actual application while net balance is calculated by factoring in the efficiency of 50% for N, 35% for P_2O_5 and 70% for K_2O
Source: Tandon 2004

Rice-based cropping systems

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

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

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

Mineralogy and K availability

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

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

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

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

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

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

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

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

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

Source: Chatterjee 2008

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

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

Changes in potassium fertility in rice-based cropping systems

Depletion of soil K reserves under continuous rice-based system has become a

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

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

Source: IPNI 2006-07

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

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

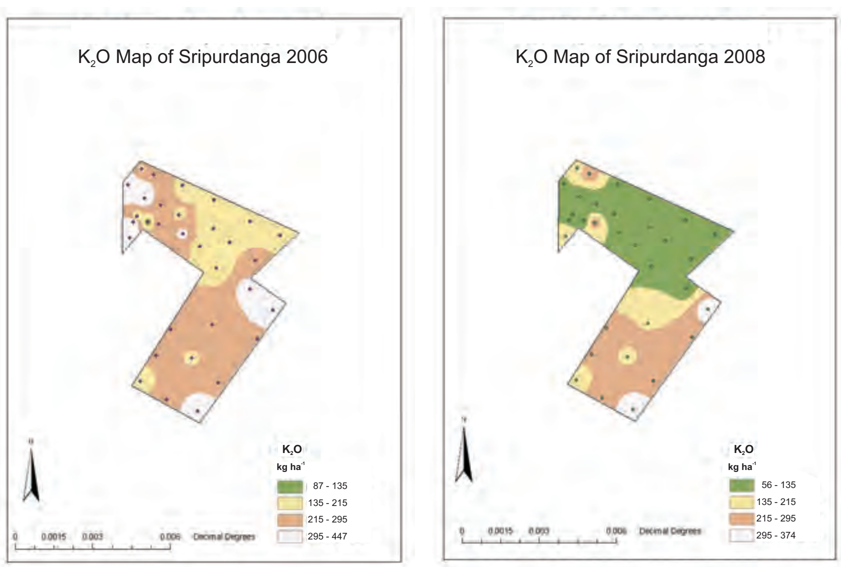
Soil Series and Location	NH_4OAc-K (mg kg^{-1})		HNO_3-K (mg kg^{-1})	
	First sampling	After 10 years	First sampling	After 10 years
Nabha, Punjab	104±54	63±41	965±25	875±23
Akbarpur, UP	125±41	71±23	1448±20	1231±18
Rarha, UP	95±33	79±20	1531±35	1497±18
Hanrgram, WB	132±53	93±16	425±16	400±19
Kharbona,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

Source: Sekhon 1999

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

Consequence of such depletion scenario across the country has led to negative potassium balance in most cropping systems, including rice-based systems. Ladha et al. (2003) analyzed yield trends in rice-wheat systems in the IGP, non-IGP areas of India and China and noted that rice and wheat yields stagnated at 72 and 85% of long-term experiments where recommended rates of NPK were applied. These

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



authors further reported that fertilizer K rates used were not sufficient to sustain a neutral K input-output balance in 90% of the long-term experiments, while all the experiments with significant yield decline had large negative K balances. It is clear that such negative K balances in soils will adversely affect the sustainability of rice-based systems and a rational approach of K management, keeping in mind the variable soil supplying power and nutrient requirements of crops/cropping systems, will be necessary to reverse the trend.

Site-specific potassium management

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

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

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

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

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

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

Adapted from Sharma (2003) after modification

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

Potassium application in site-specific manner significantly enhanced the rice-wheat system productivity in the above study. The system yield increase was associated with response rate of 8.9 kg grain kg^{-1} K_2O applied with a Benefit: Cost Ratio (BCR) of 4.3 to 13.5 depending on the location. Pooled data of location and K rates showed that benefit for K application were 5 or more in 81% cases and 10 or more in 57% cases. In rice-rice system, the response to K application was 5 kg grain kg^{-1} K_2O. Across the sites, the BCR for K application was 5 or higher in 59% cases. The authors concluded that optimum potash application can increase the productivity of the rice-rice system by 1300-1900 kg ha^{-1} and the current general K application rates need upward revision to achieve higher target yields. Gill et al. (2009) studied the level of response of NPK in major cropping systems across 32 centers located in different agro-climatic zones. The response to potassium in rice based cropping systems varied from 11.7 to 51.0 kg rice grain equivalent kg^{-1} nutrient. The oilseeds crops following rice gave response of 17.3 to 24.6 kg rice grain equivalent kg^{-1} nutrient, while in rice based cereal cropping systems, the potassium response was confined to the range of 14.0 to 16.2 kg rice grain equivalent kg ha^{-1} nutrient (Table 9).

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

Location	Optimum rates (kg K_2O ha^{-1})			Location	Optimum rates (kg K_2O ha^{-1})		
	Rice	Wheat	System		Rice	Rice	System
Sabour	75	76	153	Maruteru	93	94	188
Palampur	76	103	182	Jorhat	89	92	176
R. S. Pura	94	104	196	Navsari	72	106	186
Ranchi	82	91	179	Karjat	94	95	165
Ludhiana	102	84	188	Coimbatore	34	45	72
Faizabad	80	60	143	Thanjavur	86	82	178
Kanpur	89	66	153				
Modipuram	87	88	177				
Varanasi	85	104	171				
Pantnagar	76	77	148				

Source: Tiwari et al. 2006

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

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

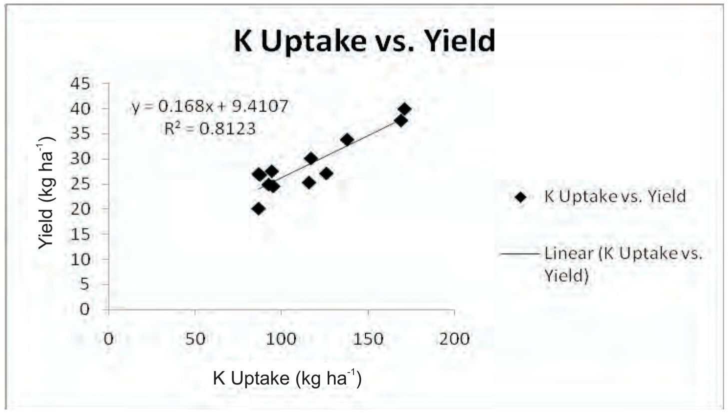
Table 9 On-farm response to nutrient in rice based cropping system

Cropping system	Response (kg rice grain equivalent kg^{-1} nutrient)			Economic response (Rs. $Rs.^{-1}$ invested on nutrient)		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O
Rice-rice	12.0	14.6	16.2	9.9	5.1	10.6
Rice-wheat	10.1	15.9	14.0	8.4	5.7	9.4
Rice-groundnut	14.3	22.8	24.6	11.8	8.1	17.6
Rice-chickpea	14.0	11.7	11.7	11.4	4.1	8.3
Rice-mustard	10.8	19.5	17.3	8.4	6.4	5.0
Rice-tomato	19.5	20.2	51.0	10.3	5.1	24.9

Source: Gill et al. 2009

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

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



Source: Mukhopadhyay et al. 2008

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

Spatial variability and GIS mapping: A key to future

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

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

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

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

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

Conclusions

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

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

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

Keywords SSNM • GIS • Soil nutrients • Spatial variability

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

Introduction

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

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

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

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

Materials and methods

Location of trials

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

Soil sampling and analysis

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

Data analysis

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

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

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

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

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

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

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

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

Results

Status of soil nutrients

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

Spatial variation of soil nutrients

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

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

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

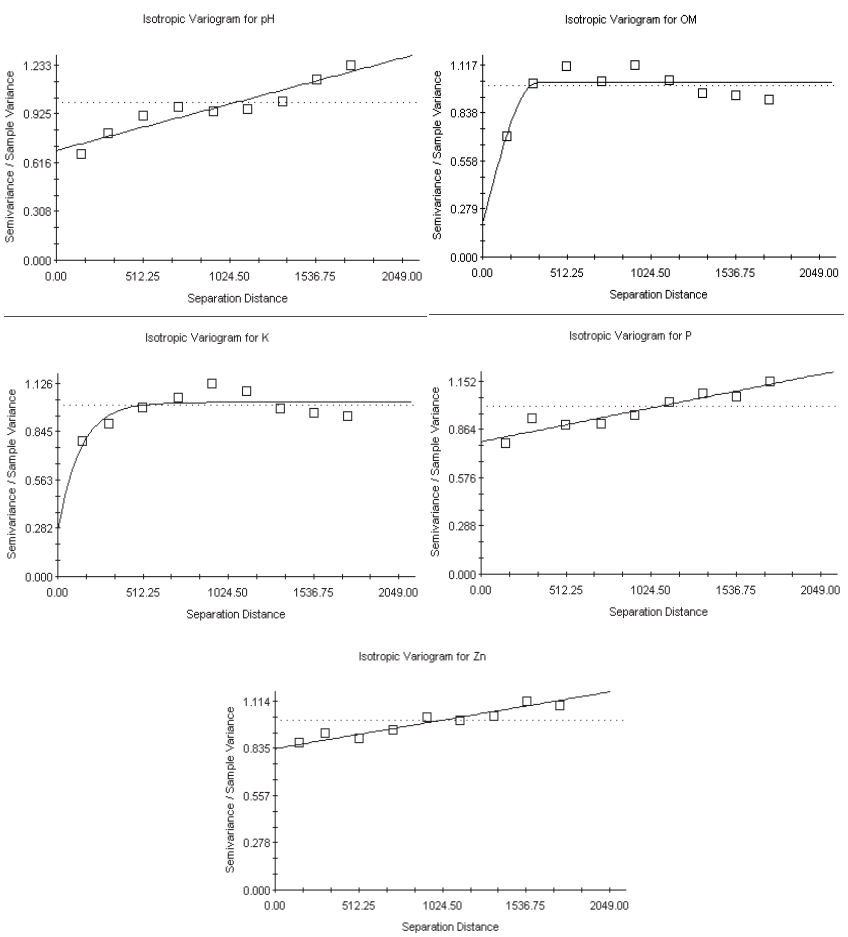
Table 2 Semivariograms analysis for soil pH, OM and nutrients in the study area

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

Spatial distribution of soil nutrients

Soil nutrient contour map was made using Kriging interpolation and using evaluation classes of the systematic approaches for soil nutrient status evaluation (Fig. 2). The contour map of soil properties may directly reflect the spatial distribution characteristic of diversified soil nutrient element; also help to understand the nutrient status to provide the foundation to rational fertilization. The integrated map was conducted with overlaying the nutrient contour map and farmer's plot map to understand soil nutrient status of each farmer's plot. If soil nutrient contents in most areas of a farmer's plot were within one evaluation class,

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



soil nutrient contents for all area of that farmer's plot were considered to fall within one evaluation class. This made it possible to improve the fertilizer recommendation system from one recommendation from 15-20 ha field to a site-specific nutrient management for a specific farmer's plot.

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

Yield and profit evaluation of SSNM

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

Discussion

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

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

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

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

Conclusion

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

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Potassium management for crops in soils of Orissa

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

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

Introduction

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

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

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

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

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

Soils of Orissa

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

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

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

Source: Agricultural Statistics of Orissa 2008

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

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

Source: Agricultural Statistics of Orissa 2008

Mineralogy of soils

Important K bearing minerals in soils of Orissa are muscovite, biotite and feldspar. Release of K to crops depends on the nature of dominating K bearing mineral. On the basis of K release power, the minerals are arranged in the order of: biotite > muscovite > orthoclase > microcline. The inherent status of K in soils of Orissa is mainly governed by the soil mineralogy. The microcline is the most common K-feldspar in the soils of Orissa (Sahu et al. 1995). In Alfisols, orthoclase constituted 9.8 to 41.1% while muscovite mica from nil to 6.1% (Table 3). The presence of high content of light minerals (orthoclase feldspar) in fine sand fractions may be attributed to moderate weathering in the environment. High temperature with alternate wet and dry season in humid sub-tropical climate of Orissa are also conducive for development of illite in the clay fractions due to alternation and partial hydrolysis of feldspar and mica (Sahu et al. 1983). The occurrence of Kaolinite in these soils is also expected due to leaching of bases. In the Inceptisols,

Table 3 Mineral composition of different soil orders of Orissa

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

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

orthoclase content varies 7 to 42.4 %. Except Shyamakhunta and Motto (saline soil), mica content varies between 1.0 to 4.8 %. These soils in general are, neutral to slightly alkaline and have high base saturation capacity with Ca^{2+} and Mg^{2+} dominating in the exchange complex. These conditions are favorable for the formation of smectites in the clay fractions (Sahu et al. 1983). Alternation of K-feldspar might have led to the formation of illite in clays. The Entisols are found in Delta area of Orissa due to deposition of silt and clay by the action of flood and contained higher amount of orthoclase (27.1 to 38.6%) and mica (1.7 to 17.4 %). High mica content in the sand fraction indicates lack of weathering and the soils are rich in K. High base saturation with mild acidic to neutral soil reaction must have favoured formation of smectites besides illites (Sahu et al. 1990)

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

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

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

Source: Nayak et al. 2001

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

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

Source: Mishra 2008

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

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

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

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

Source: Pattnayak 1992

Potassium status

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

Interrelationship of forms of K

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

Potassium transformation

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

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

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

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

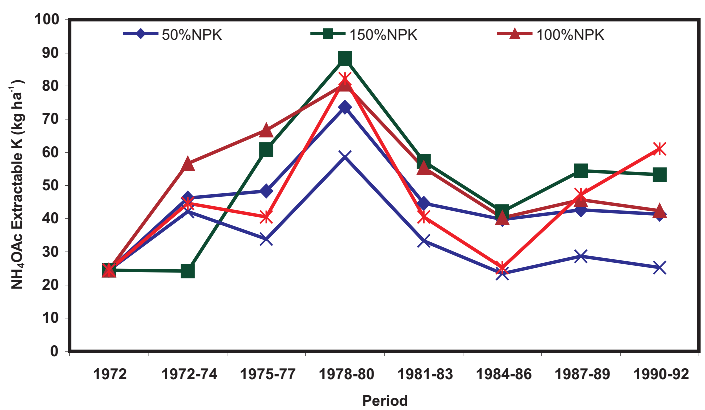
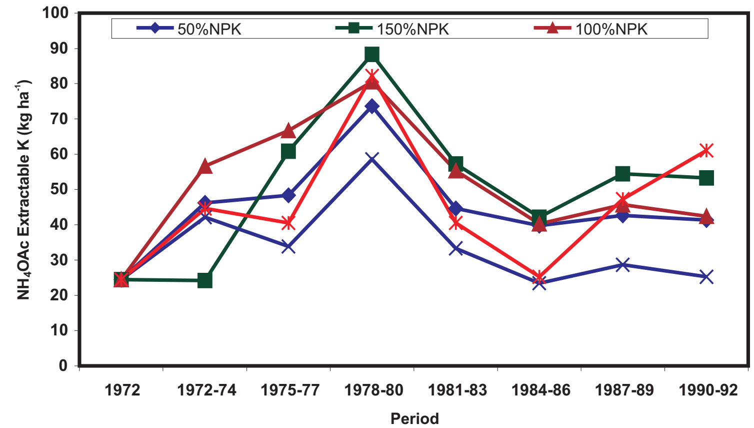
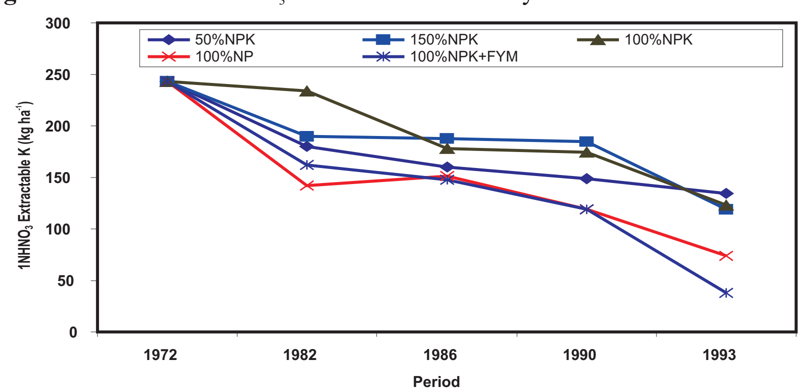


Fig. 2 Variation in NH_4OAC extractable (available) K status of soil under long term manuring at Keonjhar centre



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

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



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

Contribution of subsurface K to plant uptake

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

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

Potassium release characteristics

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

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

Crop response to applied potassium

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

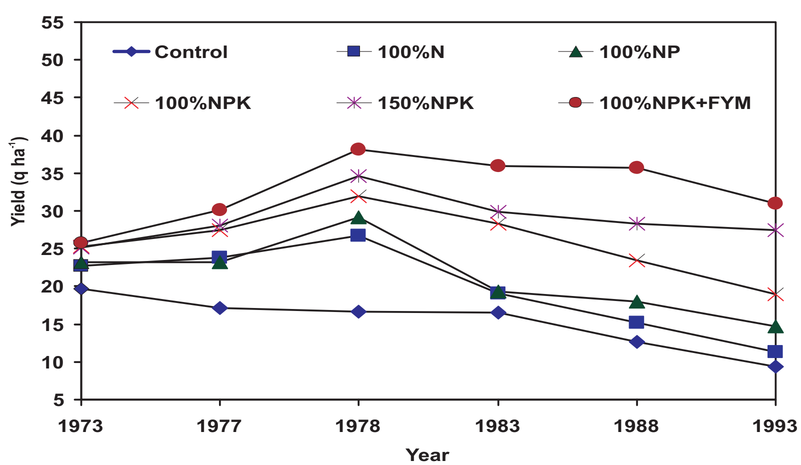
Table 7 Cumulative effect of treatments on Step -K and CR-K after 22 years of rice-rice cropping at Bhubaneswar

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

Source: Senapati 1993

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

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



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

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

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

Source: Pattanayak et al. 2008

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

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

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

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

Source: Senapati and Santra 2009

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

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

Potassium removal and balances in different cropping systems

In rice-rice cropping system over 41 cropping cycles in laterite soil of Bhubaneswar, the K uptake under optimum fertilizer application (100% NPK) was 137 kg ha^{-1} which was increased to 167 kg ha^{-1} with integrated use of 100% NPK + FYM. The mean annual K balance was negative in all the treatments (Table 10). Green manuring or incorporation of paddy straw reduces K mining in rice-rice cropping system (Pal and Dash 2009). The K removal by rice – groundnut cropping system in alluvial soils was 180 kg ha^{-1} where as in rice – green gram cropping system in laterite soils it was 170 kg ha^{-1} (Jena 2008). In general, cereals, pulses and oil seed crops removes 226, 67 and 83 kg K ha^{-1}, respectively (Panda 1995). K removal in vegetables and fruit crops was much higher than cereals, pulses and oilseeds (Senapati and Santra 2009). The K removal by vegetables

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

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

Source: Sahoo 1994

ranges between 90 to 480 kg ha^{-1}. Tuber crops like potato, cassava, sweet potato, elephant-foot yam remove about 310 to 350 kg K_2O ha^{-1}, whereas fruit crops like banana and pine apple remove 1180 and 530 kg K_2O ha^{-1}, respectively. In most of the cropping systems being practiced in India, potassium balance is negative (Rupa et al. 2003). A huge negative balance of 242.9 thousand tones of K in soils of Orissa has been reported by Misra and Mitra (2001) who suggested that dose of K for rice need to be revised from 30 to 60 kg ha^{-1} since 62% of K depletion is caused by rice.

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

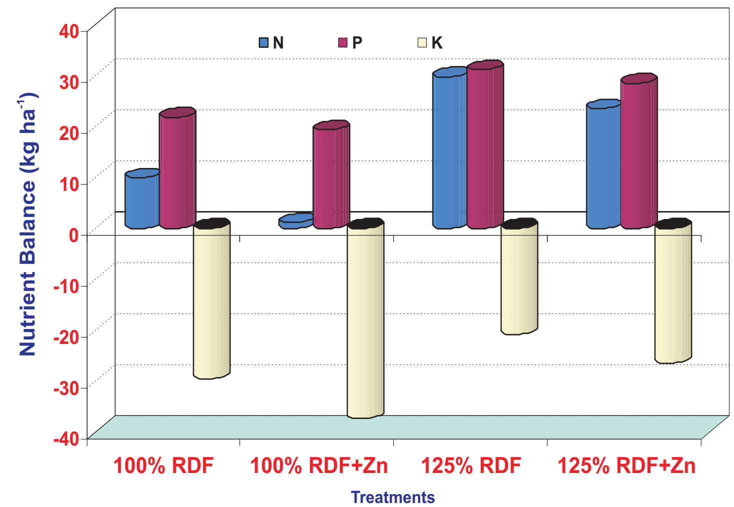
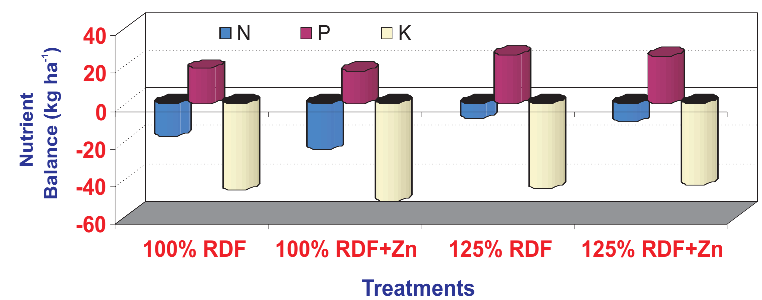


Fig. 6 Nutrient balance of rice-green gram cropping system in laterite soils of Nayagarh



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

Management of potassium

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

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

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

Conclusion

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

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

I Öborn • A C Edwards • S Hillier

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

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

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Introduction

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

The significant contribution that soil minerals can make to plant available K means that this aspect should also be considered in addition to fertiliser and manure inputs. While lack of total soil K (Tot-K) reserves (organic soils being an exception) is not often an issue, it is possible that short-term deficits of plant

available K, for example, during the later part of the pasture growing season may occur (e.g. Brady and Weil 1996). During these times the rates of exchange between various soil K sources need to be considered. Various soil K pools have been defined as, soil solution K, exchangeable K, fixed or non-exchangeable K bound in the inter-layer positions, e.g. of weathered micas, vermiculites etc., and finally structural K particularly associated with micas and K-feldspars (e.g. Sparks and Huang 1985; Sparks 1987; Huang 1989; Robert 1992). The dynamic situation that exists between the K pools determines the plant available K and is among other things influenced by plant properties such as root density and rooting depth (e.g. Haak 1981; Kuhlmann 1990; Witter and Johansson 2001), climatic conditions (soil temperature and moisture) (e.g. Holmqvist et al. 2003), soil attributes (organic acids, pH, particle size distribution etc) as well as type of K bearing minerals (e.g. Wilson 1992; 2004; Hinsinger and Jaillard 1993; Barré et al. 2007; 2008) and management practices (e.g. Singh and Goulding 1997; Simonsson et al. 2007).

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

The specific objectives were to:

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

Materials and Methods

Site and soil description

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

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

Experimental design

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

Sampling and sample treatment

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

Plant sampling and preparation

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

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

Hori-zon	Depth cm	pH[a] $CaCl_2$	C[b] %	N[b] %	S[b] %	Bulk den-sity[c]	Cl[d]	Si[d]	Sa[d]	Ca[e]	Mg[e]	K[e]	Na[e]	CEC[f]	BS[g] %	Rel root distr.
Ap1	0- 5	4.9	5.4	0.38	0.04	0.71	2	17	81	8.1	0.8	0.2	0.3	19	50	42
Ap2	5-15	5.1	4.3	0.30	0.04	0.65	1	17	82	8.2	0.3	0.1	0.1	17	51	21
Ap3	15-25	5.2	4.1	0.28	0.02	0.80	2	22	76	9.6	0.1	0.1	0.1	17	58	21
Bs	25-40	5.2	1.5	0.09	0.01	0.68	4	21	75	4.1	0.1	0.1	0.1	9	48	16
BC	40-60	5.3	-	-	-	0.73	7	25	68	5.2	0.1	0.1	0.1	10	52	~0

[a]Soil pH in 0.01 M $CaCl_2$, soil:solution ratio 1:2; [b]Total-C, -N and -S (weight %) – finely ground soil was analysed on a Leco; [c]The soil is formed in glacial till where gravels and stones were abundant (>2mm) and thus the bulk density for the <2mm was low; [d]Pipette method, samples dispersed in deionized water with ultrasonic probe; [e]10 g soil 250 ml 1M NH_4Ac (pH 7) (Rowell 1994), Ex-Ca, Ex-Mg, Ex-K and Ex-Na analysed by ICP-AES. [f]$CEC_{pH\,7}$ = sum of Ex-cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) and acidity. Acidity: mix 5 g soil with 1M Ba-acetate (pH 7) and titrate with $Ba(OH)_2$ to pH 7. [g]Base saturation (BS) = (Ex-cations/CEC_{pH7})*100.

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

Soil sampling and sample preparation

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

Soil bulk density

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

Plant and soil analyses

Plant analyses

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

Soil analyses

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

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

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

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

K input-output mass balance calculations

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

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

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

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

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

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

Statistical analyses

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

Results

Grass biomass production and K concentrations

Herbage yield

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

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

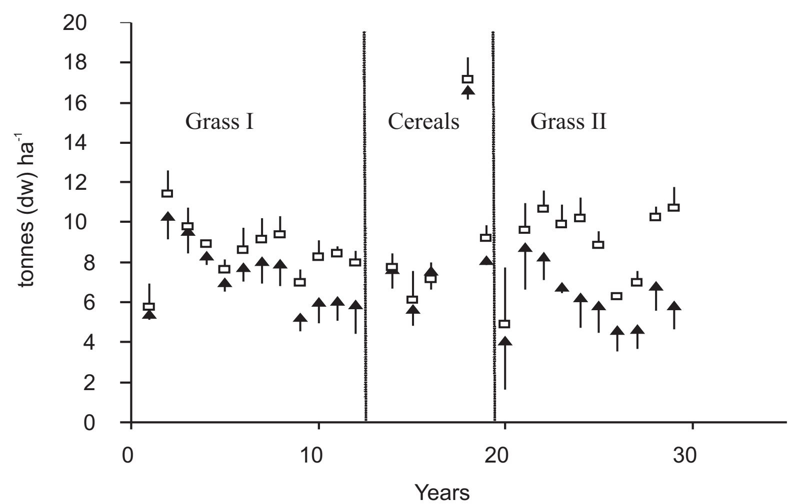


Figure 1a

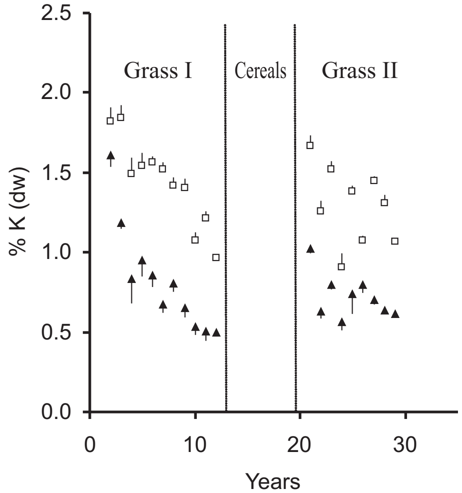


Figure 1b

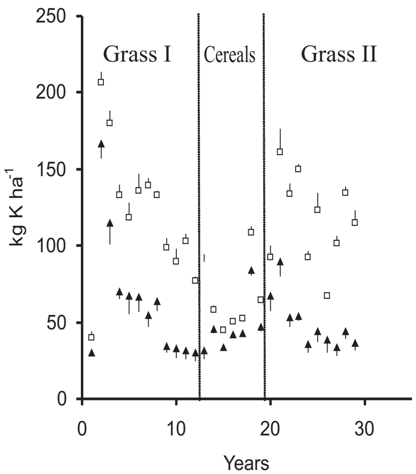


Figure 1c

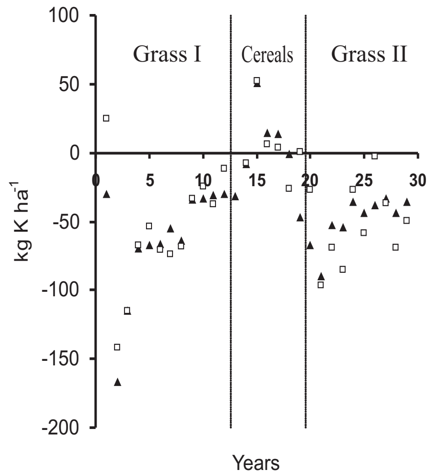


Figure 1d

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

Herbage K concentrations

The annually averaged herbage K concentration decreased significantly in K0 and K65 treatments during both Grass I and II periods (Fig. 1b). The K65 herbage had a

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

K dynamics during the growing season

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

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

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

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

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

Potassium off-take and K input-output mass balances

Annual K removal and net off-take by biomass harvest

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

Input-output K mass balances

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

Acetic acid extractable soil K and its turnover rates

Acetic acid extractable soil K

At the start of the experiment the K status of the soil was moderate to low and over time it dropped into very low status (MISR/SAC, 1985). The long-term dynamics of Ac-K in the surface soil (0-15 cm) showed an annual variation but also a clear difference between the years with grass compared to those with cereals, the Ac-K concentration being lower under grass (Fig. 2). The general trend was similar for

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

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

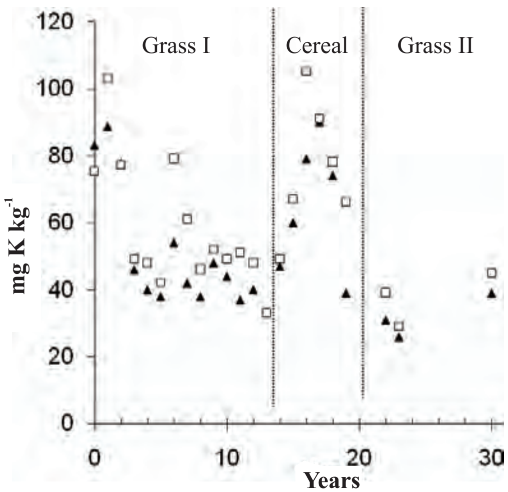
[a]During the period with cereals a basal NPK dressing was applied, except for 1987 when the 0 and 65 kg K treatments were applied

both treatments, but the K0 plots overall showed a lower Ac-K than the K65 plots. A very dry summer could be a possible explanation for the high Ac-K concentrations recorded by the end of the 6th year of Grass I (1976). Ac-K was only determined on three occasions during Grass II, with the final sampling taking place in spring, and although based on very few observations the concentrations appeared to be at similar (or lower) levels to those measured during the Grass I phase.

Soil K turnover rates

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

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



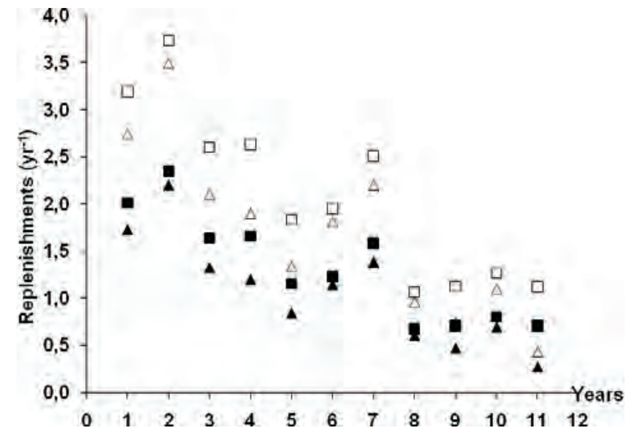
and the same time periods the ratio was lower, 1.4 (K0) and 1.1 (K65) for years 2-7, and 0.7 (K0) and 0.5 (K65) for years 8-11, showing that the Ac K pool was initially replenished in less than a year and thereafter took between 1.5 and 2 years to replenish (Fig. 3).

Soil K resources and their relative contributions to plant available K

Potassium in the soil profile (rooting zone)

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

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



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

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

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

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

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

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

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

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

Long-term budget calculations and changes in soil K pools

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Discussion

While somewhat extreme, the zero (K0) and low (K65) fertiliser K treatment and

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

Potassium – the limiting nutrient for plant growth

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

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

Plant available soil K

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

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

Annual K off-take and soil K pools

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

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

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

Estimation of K release from soil resources

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

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

neutral pH values (e.g. Fanning et al. 1989).

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

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

Conclusions

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

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

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State-wise approach to crop nutrient balances in India

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

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

Introduction

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

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

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

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

Nutrient balance scenario in major states of eastern India

Assam

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

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

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

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

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

supplementary nutrient addition are the keys to uphold productivity at high and sustained level.

Bihar

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

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

Jharkhand

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

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

Orissa

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

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

West Bengal

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

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

Nutrient balance scenario in major states of northern India

Haryana

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

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

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

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

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

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

encouraging combined use of fertilizers with organic manures, crop residues, green manuring and biofertilisers.

Punjab

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

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

Uttar Pradesh

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

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

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

Nutrient balance scenario in major states of southern India

Andhra Pradesh

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

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

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

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

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

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

Karnataka

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

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

Kerala

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

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

Tamil Nadu

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

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

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

Nutrient balance scenario in major states of western India

Gujarat

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

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

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

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

a* Inputs through fertilizers and organic manures considered. Contribution of BNF deducted for calculating N removal
b* Additions through only fertilizer nutrients considered

Madhya Pradesh

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

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

Maharashtra

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

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

Rajasthan

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

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

Conclusions

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

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

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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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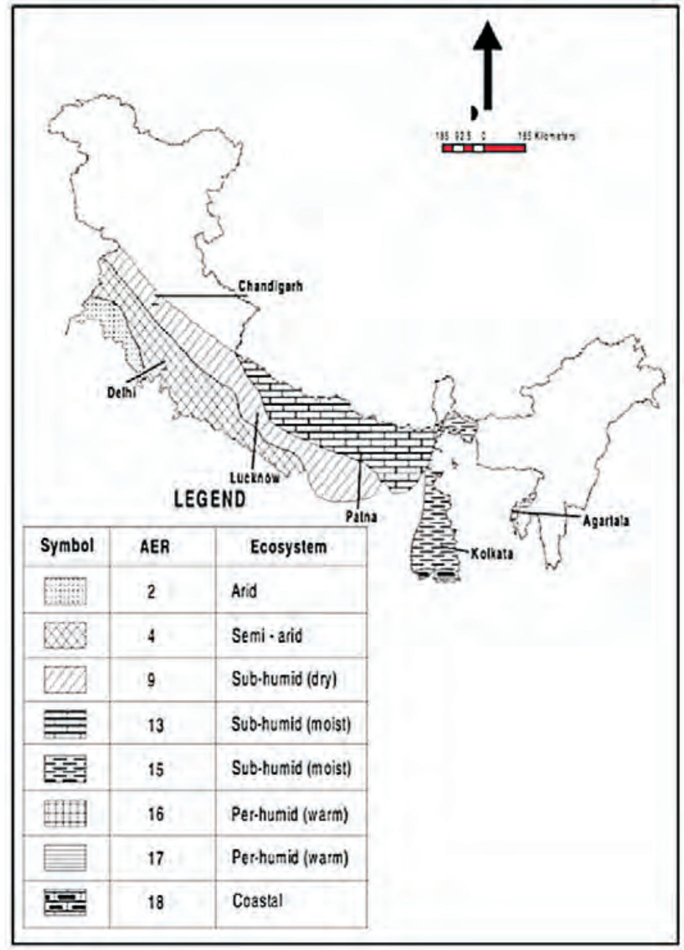
Introduction

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

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



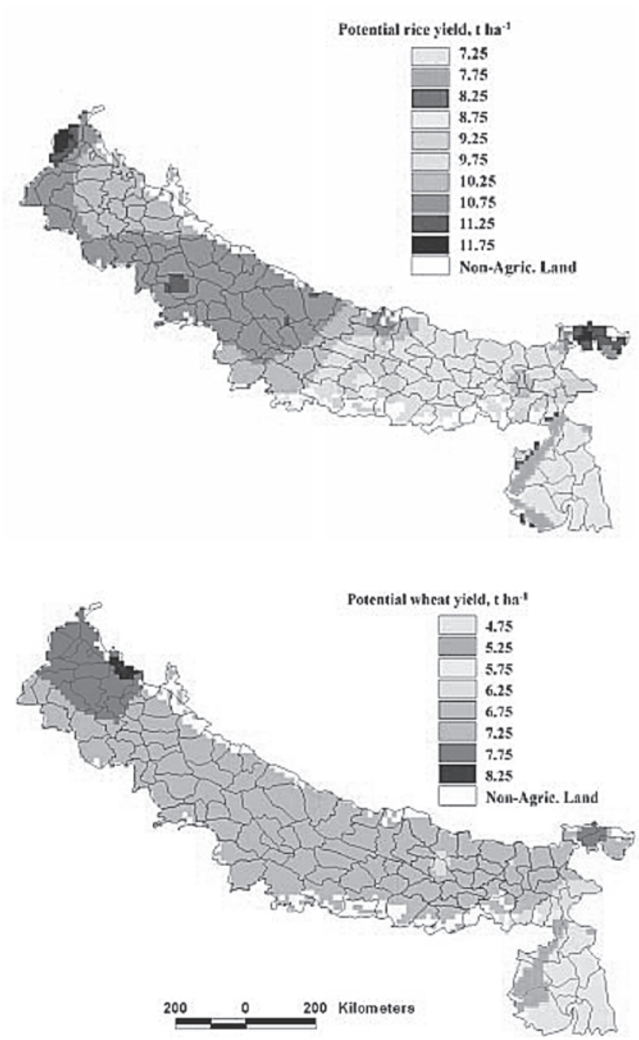
natural resources, (iii) declining water level, (iv) loss in soil fertility, (v) nutrient imbalance/deficiency, (vi) drainage congestion, and (vii) loss in soil carbon (Abrol and Gupta 1998; Bhandari et al. 2002).

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

Dinesh K Benbi • MS Brar

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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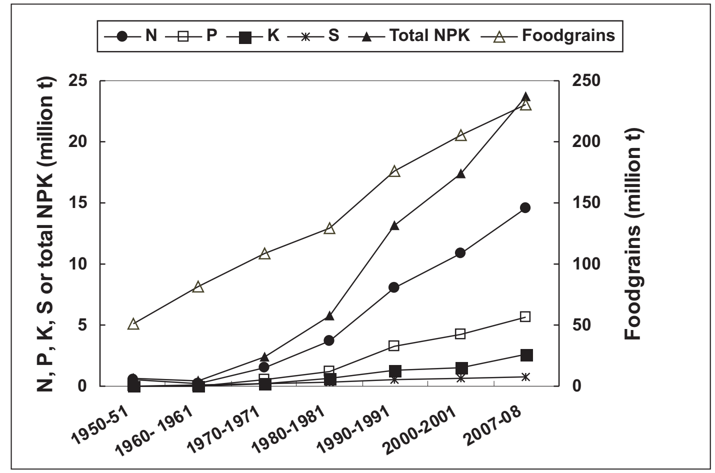
food crops responsive to fertilizer nutrients. The food grain production, which was only 82 million tonnes (mt) during 1960/61 before the green revolution period increased to 130 mt in 1980-81 and 230 mt in 2007-08. The large increase in food grain production during the last four decades has resulted 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)

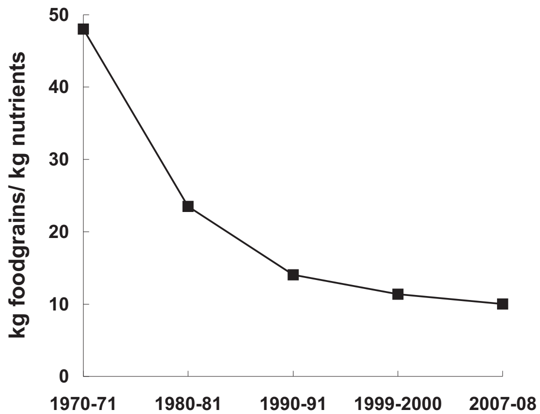
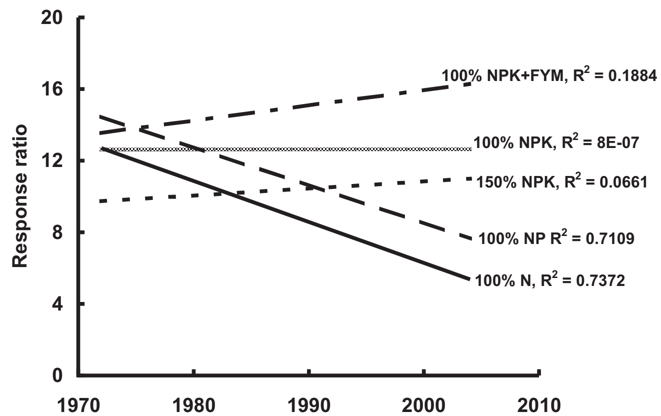
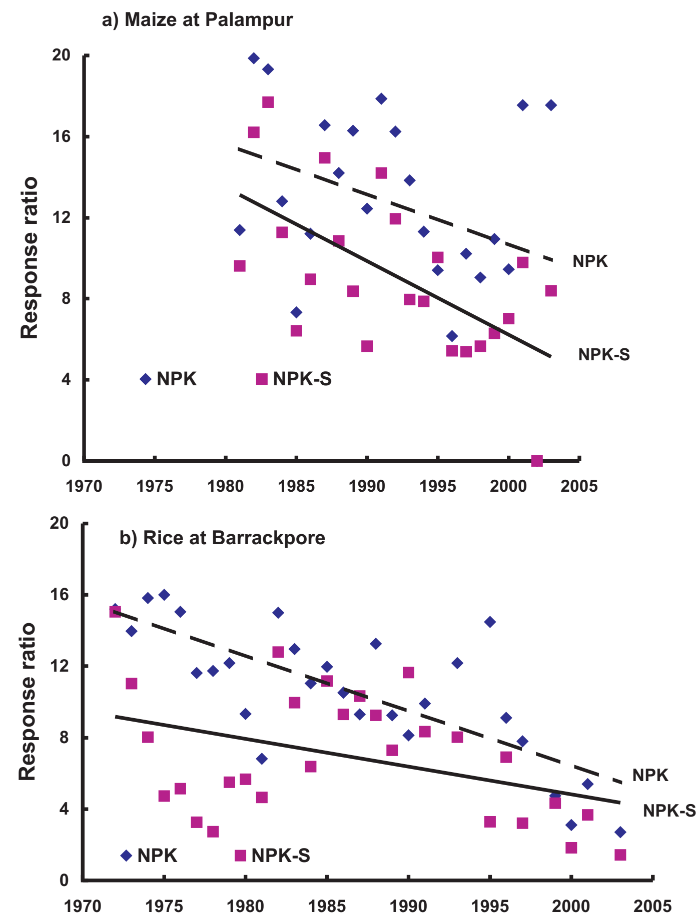


Fig. 3 Nutrient response ratios (kg grain kg^{-1} nutrient) in cereals. Drawn from long-term fertilizer experiments data averaged over 1972-2003 and several locations of rice, wheat, maize and finger millet (Samra 2006)



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

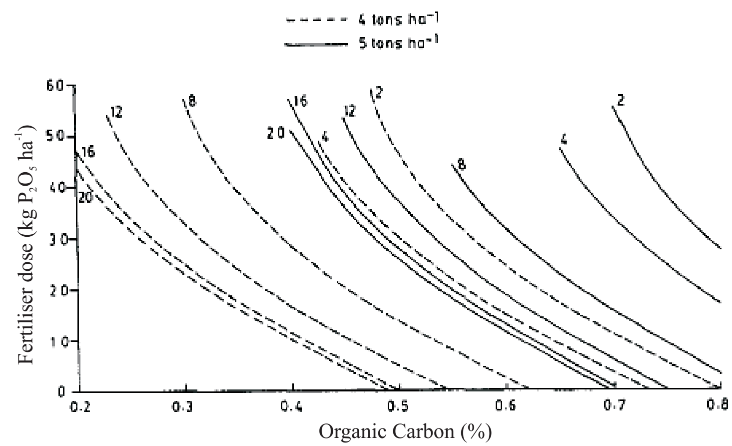
The soil-test based fertilizer recommendations (STRD) are based on classification of soils into low medium and high categories based on soil test values for plant available N, P and K. The fertilizer dose is increased by 25% over the GRD if soil is testing low and decreased by 25% if soil is testing 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

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)



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.

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].

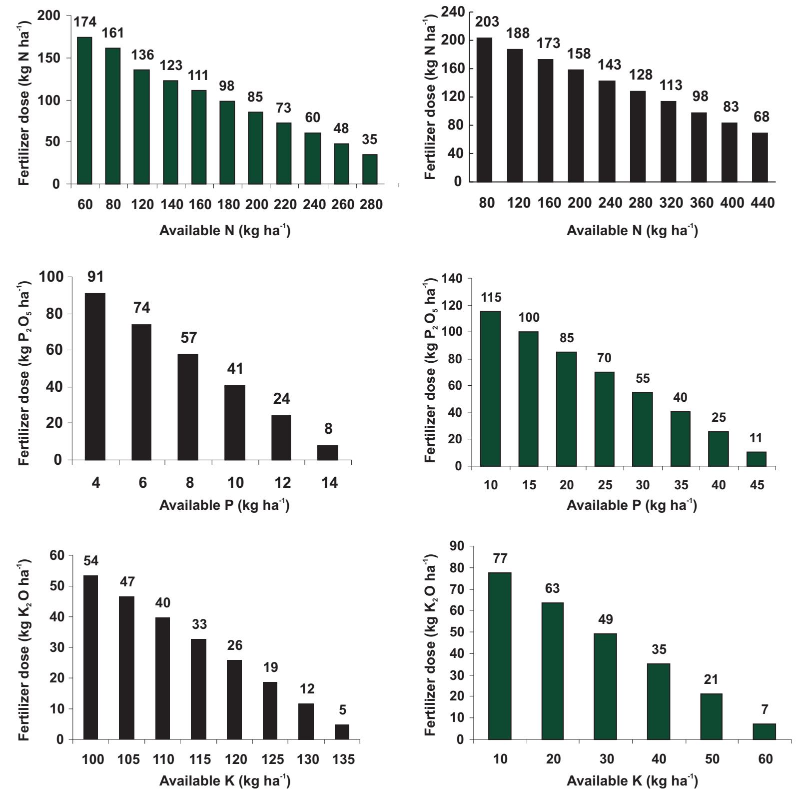
NR (kg nutrient / Mg grain)	=	X_f / GY	(1)
CS	=	X_0 / STV_0	(2)
CF	=	$(X_f - (STV_f \times CS))/A_f$	(3)
Fertilizer dose (kg ha^{-1})	=	$\dfrac{(NR*T) - (CS \times STV)}{CF}$	(4)

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).

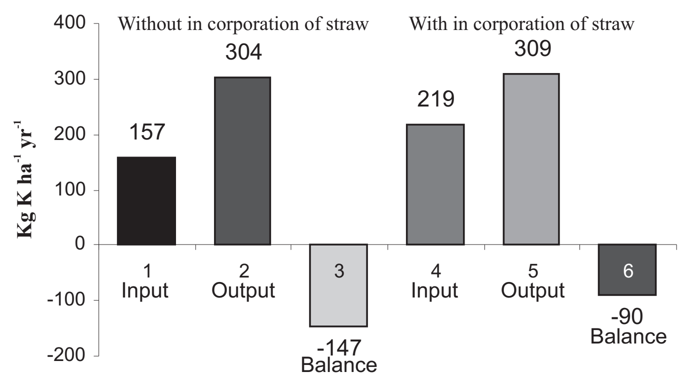
Table 3 Potassium removed by 13 crop cycles (maize-wheat) and its effect on exchangeable- and non-exchangeable K in soils (1970-71 through 1983-84) (Adapted from Singh and Brar 1986)

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),

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

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 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

MS Islam

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

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

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.

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	Grain yield (t ha^{-1})			
(kg 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

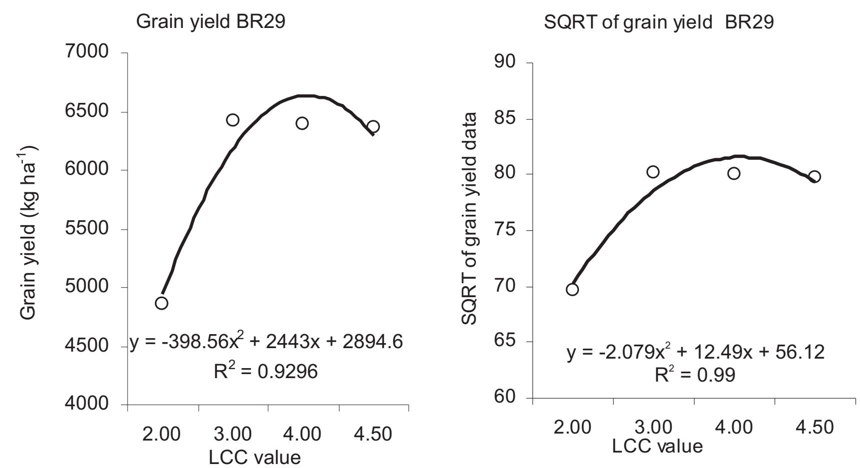
Extension activities on balanced fertilization have been undertaken by various research institutes, GO/NGOs and development partners through out the country. Technologies generated on balanced fertilization practices for different crops and cropping patterns at the various National Agricultural Research 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,

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

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.

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.

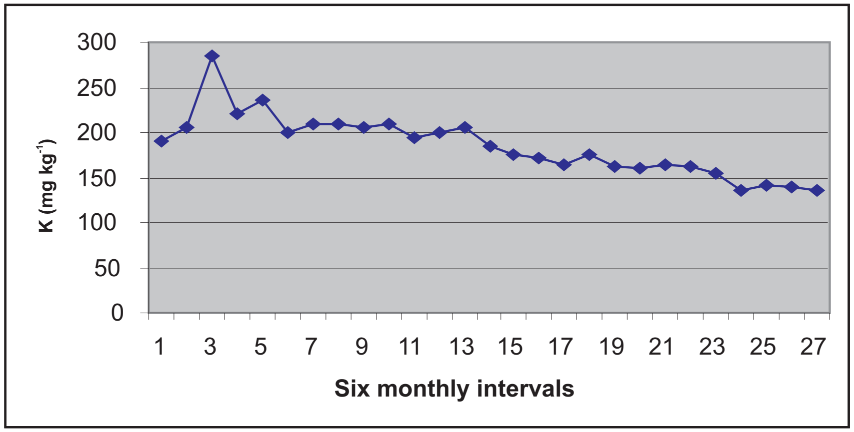
Zone	1990			2005			Per cent decrease
	No. of samples	Mean	SD	No. of samples	Mean	SD	
Rainfed	1500	114	34	1550	106	21	7
Rice	1400	176	71	1645	132	90	33
Central	2670	295	153	3200	198	83	49
Cotton	1658	210	15	2280	165	32	27

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

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

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.

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-

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

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.

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

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

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 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 recom-mendation	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

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

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 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.

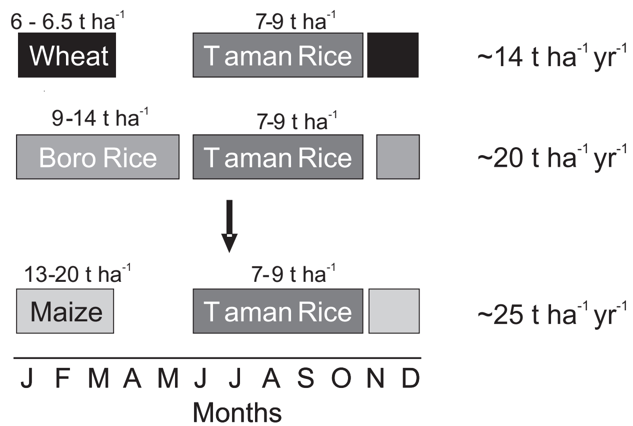
Table 11 Simulated Yp (t ha^{-1}) and growth duration (d) for rice and maize planted during farmers' preferred planting times in Sadar Upazilla, Kustia District, Bangladesh (Source: Buresh and Timsina 2008)

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

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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

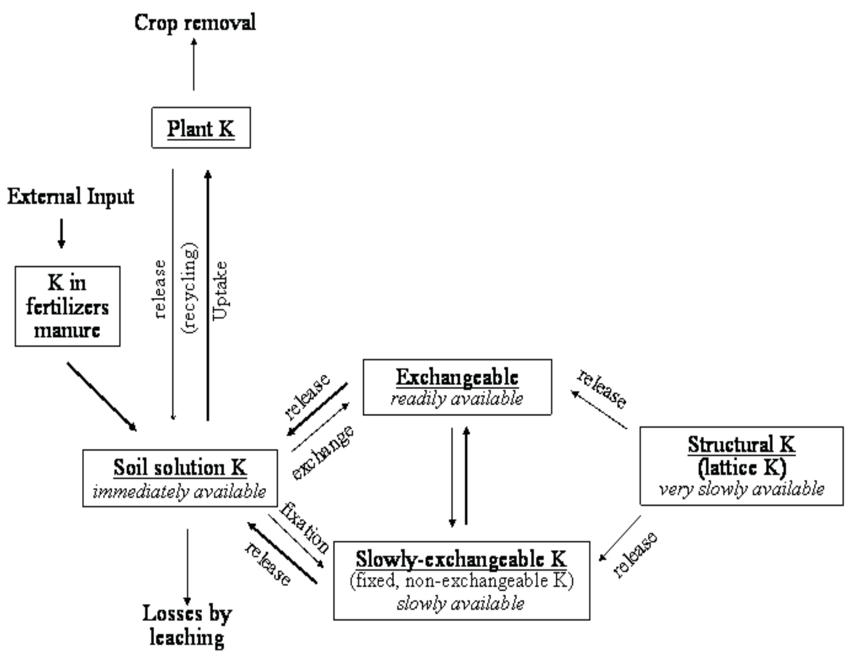
Kiwi orchard	Visual symptoms (June 2009)	Classification by soil analysis	Leaf analysis (% in leaf DM)
"Gurini" (sandy soil)	Mg deficiency	K: high-very high Mg: low-very low	K: 1.49 (adequate) Mg: 0.43 (low)
"Dalle" (clay loam soil)	K deficiency	K: very low Mg: very high	K: 0.80 (low) Mg: 0.67 (high)

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

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

proved beneficial, simultaneously lowering loss of K by leaching and raising efficiency of use of the K fertilizers applied (Kolar and Grewal 1994).

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_4OAc, NH_4Cl, $CaCl_2$, 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

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}

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.

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.

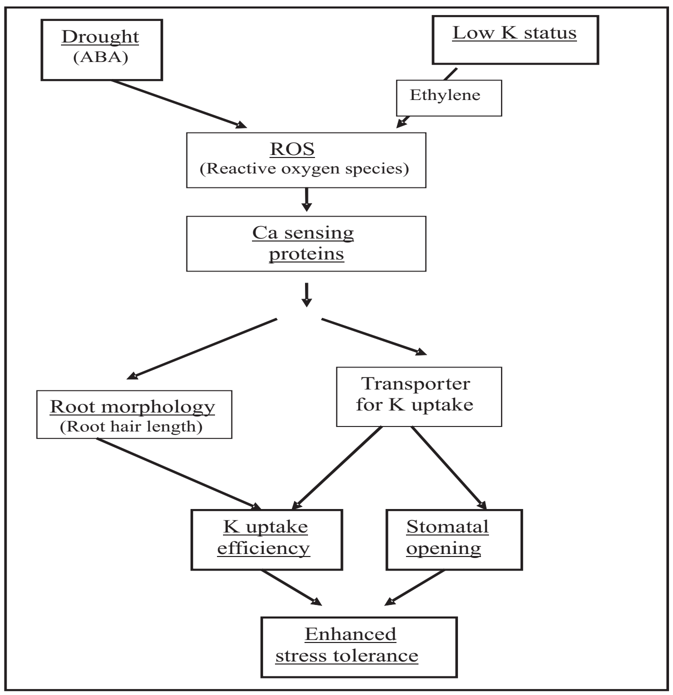
It is well documented that K deficient plants are more susceptible to high light intensity with associated occurrence of photooxidative damage such as chlorosis and necrosis (Marschner and Cakmak 1989). One reason for this enhanced ROS formation under high light is the inhibition of photosynthesis and 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.

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

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

raising frost resistance.

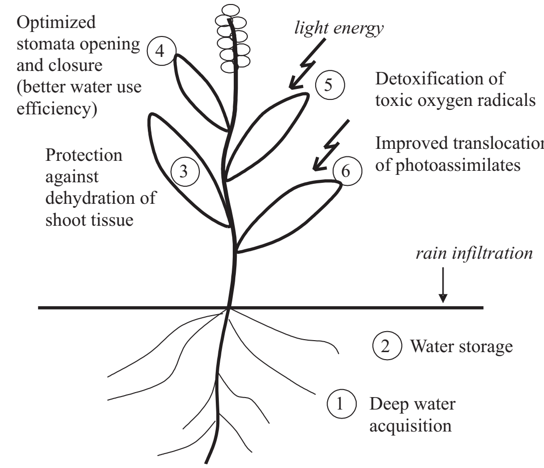
A major function of K as an osmoticum is the maintenance of a high concentration of K in the cell sap thus lowering its freezing point. Additionally the activities of numerous enzymes which might play a part in frost resistance are also dependent on adequate K cytoplasmic concentration (Kant and Kafkafi 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

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".



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").

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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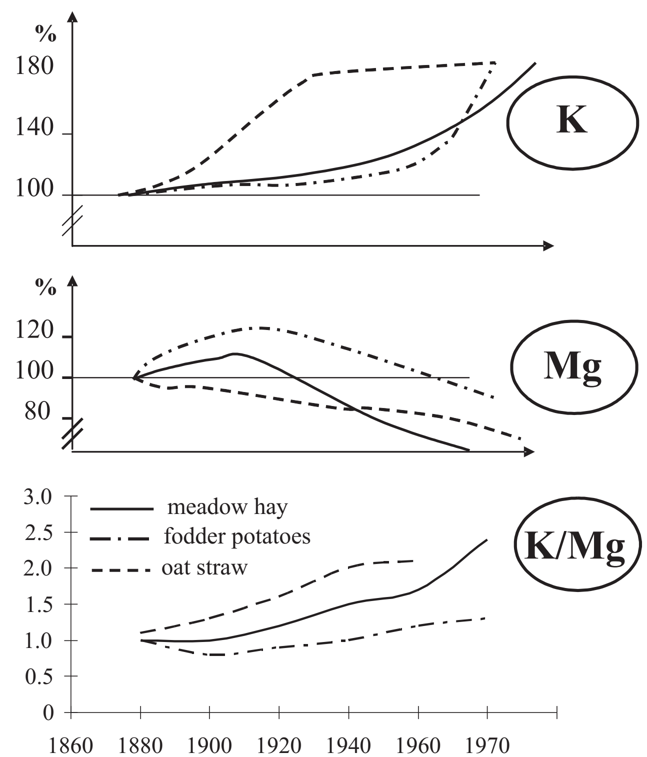
Potassium/magnesium ratio in food and fodder

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%

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)



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).

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

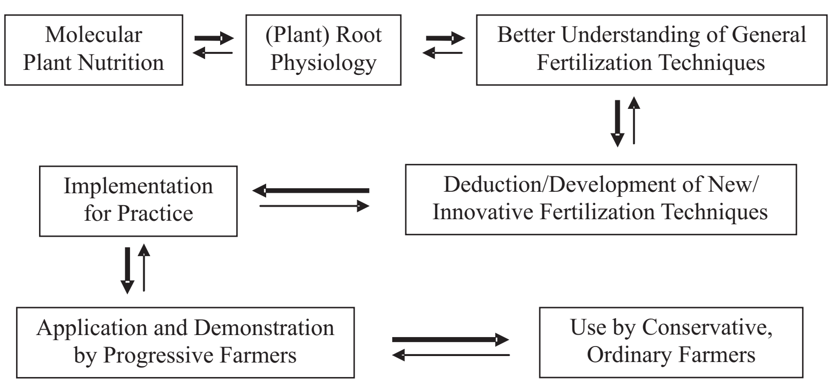
Cadmium (Cd) is an undesirable heavy metal in food products because of its high toxicity. Contradictory reports appear in the literature on the effect of K fertilizers on Cd availability in soils particularly when applied in the chloride form (Grant et al.1996; Umar et al 2008; Blank 2009). Chloride 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

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

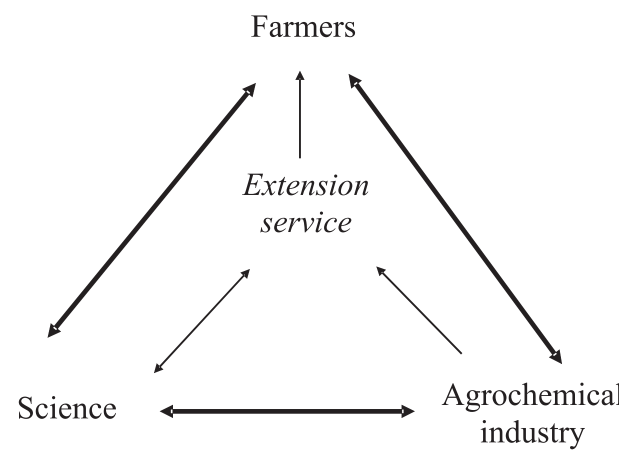


especially N and Mg. The reported mitigating effects of particular micronutrients acting in conjunction with K on various stresses is of immediate importance to crop production and requires investigation. The various proposed basic and applied research aspects relating to adequate frost resistance are 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.

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 scientist**s,** 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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Crop mineral nutrition under drought conditions

Zed Rengel

Introduction

Climate change will result in increased variability of precipitation. Moreover, many areas in the world (e.g. Western Australian wheat belt) are projected to have reduced rainfall, causing more frequent and longer droughts. Hence, in rain-fed agriculture, measures designed to increase the capacity of roots to take up water and nutrients from soil with limited water availability are needed. This review will concentrate on 1) breeding for improved root architecture and function, 2) fertiliser placement to encourage root proliferation deeper in the soil profile, and 3) hydraulic lift of water from wet into dry soil via roots.

Breeding for improved root architecture and function

Complex plant structures like roots have two developmental pathways: (i) intrinsic (governing the basic architecture and the limits of plasticity) that is determined genetically for a particular species, and (ii) response pathway determined by environmental cues (Malamy 2005). These two pathways combine in intricate ways to create a highly complex 3-D root structure influenced by genetics as well as the availability of resources in the heterogeneous soil environment (Baddeley et al. 2007). Although diffusion coefficients of nutrient ions are reduced in dry soil, many reports suggest that the uptake of soil immobile nutrients is predominantly affected by reduced root growth as soil dries out (Crabtree et al. 1998; Rose et al. 2008).

Root systems are fundamental to crop productivity (Dunbabin 2007; Malamy 2005). In Australia, crop root systems are poorly adapted to soils, resulting in yields averaging only 50 percent of the potential, with the major limiting factors being poor soil water holding capacity and nutrient deficiencies (Rengasamy 2002; Wong and Asseng 2006). Growing cultivars tolerant to soil-related stresses would be an economically- and environmentally-favourable solution most readily adopted by farmers (Rengel 2005). Hence, successful crop genotypes in the future will need to have enhanced efficiency of capturing water and nutrients from the increasingly hostile soil environments (De Dorlodot et al. 2007).

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Targeted development of crop genotypes with increased efficiency of water use (Liu et al. 2007; Manschadi et al. 2006; Ober et al. 2005) and nutrient capture (Rengel 2005) hinges on a better understanding of root structure and function (Wang & Smith 2004). In soybean genotypes, increased capacity to take up water from deep (1.1 m) soil horizons in the field was linked to increased yield potential (Ober et al. 2005); similar connection was made for upland rice (Kondo et al. 1999) and also wheat in western and southern Australia (Wong and Asseng 2006).

Because genetic loci for root properties overlap with those associated with crop productivity in the field (Steele et al. 2007), identifying genetic loci and eventually molecular markers to facilitate marker-assisted selection for root traits will result in the selection of genotypes with higher productivity in the field based on more efficient capture of water and nutrients (De Dorlodot et al. 2007). Indeed, marker-assisted selection for the root-related genetic loci has been used to alter root architecture and increase grain yield in the field-grown rice (Steele et al. 2007) and also to increase root size and grain yield in maize (Landi et al. 2005). However, wide-scale use of root-related genetic information in breeding is hampered by relatively small mapping populations and inaccurate phenotyping (De Dorlodot et al. 2007).

Phenotyping of root traits in breeding programs is presently hindered by the structural and functional complexity of root systems in heterogeneous soil environments (Doussan et al. 2003; Pierret et al. 2006; Valizadeh et al. 2003), requiring multidisciplinary analysis of root functioning in soil, characterisation of factors limiting soil-root interactions in specific environments, and identification of root parameters that represent potential solutions. These requirements can be met by modelling, providing that models: (i) are 3-D and time-dynamic, (ii) integrate biological, physical and chemical processes occurring in soil, (iii) enable simulations of scenarios beyond those directly observed, and (iv) are capable of simulating these scenarios in a dynamic environments that vary in time and space (De Dorlodot et al. 2007).

It is still unknown which phenotypic traits are desirable in achieving increased efficiency of water and nutrient capture from the drying soil environments (Walk et al. 2006). However, defining optimal root systems can be done via simulation computer models, eg. ROOTMAP as an interactive model of root structure and function (Dunbabin et al. 2002b). ROOTMAP excellently matches the patterns of root growth and nutrient uptake observed in the field (Dunbabin et al. 2002a) and is uniquely able to search for optimality of root structure and function regarding nitrate and P capture in variable seasonal conditions (Dunbabin et al. 2003; 2004; 2006).

Manipulating root distribution in the soil profile by fertiliser placement

In water-limited environments where the topsoil is prone to drying, placing fertilisers deeper in the soil profile could increase nutrient acquisition by plants because fertilisers would be in the moist soil for a longer part of the growing season (Ma et al. 2009). There are many reports on the yield benefit from deep fertiliser placement (Crabtree 1999; Hocking et al. 2003; Jarvis and Bolland 1991). However, the effectiveness of deep fertiliser placement is influenced by soil texture, tillage, fertilising history, nutrient mobility, and crop species. In addition, when subsoils feature toxicities such as boron or salt, increasing root proliferation into the subsoils by placing fertilisers deep may exacerbate toxicity problems (Ma et al. 2009).

Roots can respond to localised nutrient availability by increasing the rate of nutrient uptake, and/or by root proliferation in the enriched zones. Frequently, the combination of these two is involved in the plastic responses of a root system to heterogeneous nutrient conditions (Dunbabin et al. 2001a; b). Compared with uniformly mixed fertiliser, root proliferation occurs in the vicinity of a fertilised band (Ma et al. 2007; Trapeznikov et al. 2003), but not too close because of toxicity caused by high nutrient concentrations (Zhang and Rengel 1999; 2002).

Hydraulic lift of water from moist deep soil layers into dry shallow layers

In agricultural systems with little soil mixing (no-till or minimum tillage) and placement of fertilisers near the seed, vertical stratification of nutrients may occur (with accumulation of nutrients in the topsoil (Howard et al. 1999). Between rainfall events, nutrients in the topsoil could become unavailable as the soil dries. In such instances, hydraulic lift may play a vital role in nutrient acquisition (Rose et al. 2008).

Hydraulic lift is defined as the root uptake of soil water from areas of high water potential (generally subsoil) and subsequent release into areas of low water potential (generally topsoil) by roots at night (Caldwell et al. 1998). Hence, hydraulic lift may maintain the root function and nutrient uptake in relatively dry soil. Hydraulic lift could be maintained even in soils that are as dry as having only 1 percent (w/w) moisture (Rose et al. 2008). There are however, both positive (Liebersbach et al. 2004; Rose et al. 2008; Valizadeh et al. 2003; Wan et al. 2000) and negative reports (Crabtree et al. 1998) with respect to hydraulic lift facilitating nutrient uptake from relatively dry soils.

Overnight, pearl millet lifted up to 27 g kg^{-1} soil (Vetterlein and Marschner 1993) and wheat ~25 g kg^{-1} soil (Valizadeh et al. 2003), but canola only 2-3 g kg^{-1} soil (Rose et al. 2008). This difference might have been caused by differential root density (greater in case of highly branched root system of cereals vs. taprooted system of canola). Increased localised supply of P fertiliser (compared with nil fertiliser) resulted in wheat plants lifting more water and taking up more P (Valizadeh et al. 2003).

Conclusions

The importance of enhanced plant capacity to take up water and nutrients from soil is becoming increasingly important in rain-fed agriculture, especially in areas that are getting drier due to climate change and as water resources become scarcer and more expensive. A long-term strategy to dealing with such problems is to breed new cultivars with enhanced root architecture and function for particular drying environments. In addition, deeper fertiliser placement and enhanced plant capacity for hydraulic lift might contribute to increased uptake of nutrients from drying soil.

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Phosphorus acquisition efficiency: Root morphology and physiology

Hans Lambers

Western Australia was a part of Gondwanaland, and some of the most ancient parts of the Earth' crust can be found here. The rocks are up to 3.6 billion years old, with some of the sediments being as old as 4.3 billion years. Other parts of the landscape originated more recently from calcareous marine deposits. Therefore, the soils of Western Australia are amongst the most heavily leached and nutrient-impoverished in the world. Moreover, the soils on lateritic profiles tightly bind phosphate, so that, phosphorus (P) is also poorly available to plants that are not adapted to these conditions. The southwest of Western Australia is also one of the world's hotspots of higher plant species diversity. Therefore, this environment offers a unique opportunity to study plant adaptations to nutrient-poor conditions.

A relatively large proportion of species from the P-poor environments in Western Australia cannot produce an association with mycorrhizal fungi, but instead, produce 'root clusters' . Root clusters are an adaptation both in structure and in functioning; they release large amounts of exudates, in particular carboxylates. Root-cluster-bearing Proteaceae in Western Australia occur on the most P-impoverished soils, whereas the mycorrhizal Myrtaceae tend to inhabit the less P-impoverished soils in this region .

The functioning of 'proteoid' root clusters in Proteaceae and Fabaceae has received considerable attention. 'Dauciform' clusters in Cyperaceae have been explored less, but they appear to function in a similar manner as 'proteoid' clusters. Research on the physiology of 'capillaroid' root clusters in Restionaceae has yet to be published.

Root-cluster growth in species of the Cyperaceae, Fabaceae and Proteaceae is systemically stimulated when plants are grown at a very low P supply, and suppressed when leaf P concentrations increase. Proteoid root clusters in Fabaceae and Proteaceae and dauciform clusters in Cyperaceae are short-lived structures, and both release large amounts of carboxylates during an 'exudative burst' at rates that are considerably faster than reported for non-specialised roots of a wide range of species. Root clusters play a pivotal role in mobilisation of P from P-sorbing soil.

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Because the world P reserves are being depleted whilst vast amounts of P are stored in fertilised soils, there is a growing need for crops with a high efficiency of P acquisition . Some Australian native species as well as some existing crops have traits that would be highly desirable for future crops. The possibilities of introducing P-acquisition efficient species in new cropping and pasture systems are currently being explored. In addition, possible strategies to introduce traits associated with a high P-acquisition efficiency into future crop species are considered promising.

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Potassium nutrition and its effect on quality and post harvest properties of potato

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Potato is a high-value crop with world-wide significance. Potato production was increasing continuously during the past decades. Today, China, Russia and India are the leading potato producers. The annual per capita consumption of potato is 31.3 kg. The potato is a multi-purpose crop widely used as table potato, for processing (crisps, chips), as seed potato and for starch production and other industrial uses (plastics, alcohol, energy). Application of potassium to potato improves the quality parameters such as starch content, contents of protein, citric acid, ascorbic acid, storage attributes such as shell strength and resistance to tuber damage as well as resistance to black spot incidence and after cooking discoloration.

Potassium is important in many physiological processes that contribute to tuber quality, and countering strees. Some of them are:

- production, translocation, conversion and storage of carbohydrates through enzyme activation
- water use efficiency – potatoes grown with adequate K supply use less water per kg of tubers and withstand drought periods
- resistance to stress (frost, heat impact) and diseases
- tuber quality and processing characteristics.

The distribution of K varies largely in different parts of potato. About 76 percent K is accumulated in tubers, 18 percent in leaves, 4 percent in stem, and 2 percent in roots. Potassium sufficiency-level varies in different parts of potato plant. At bud stage K-sufficiency (K- percent of dry matter) range varies from 4.5 to 7.0 percent, at start of flowering from 4.0 to 6.4 percent, at end of flowering from 3.7 to 6.1 percent and at tuber formation from 3.5 to 5.7 percent. Potato is a heavy feeder of potassium. A crop with tuber yield of 40 t ha^{-1} removes about 300 kg K ha^{-1}, out of which 250 kg is removed by tubers.

Occurrence of black spots is a serious quality-reducing factor in potato. The formation of black spots depends on both external and internal factors. The external factor includes growing conditions eg. site, fertilization, water supply, harvest conditions, post harvest treatment and storage conditions. Variety and

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maturity of tubers are another important factors. Among internal factors are free phenolic acids, organic acids (pH), other phenolic compounds and activities of enzymes besides mineral content.

The importance of K for the tuber quality is due to the fact that K is involved in the formation of free phenolic amino acids, organic acids (pH) and other phenol compounds. Potassium induced formation of citric acid for example prevents tubers from the occurrence of black spots by inhibiting the formation of grey ferric complexes inside the tuber tissue. The discoloration occurs due to combination of Fe with chlorogenic acids, which under oxidized conditions forms grey coloured ferric complexes. By Increasing the foliar K content from 2 to 4 percent through adequate K supply, black spot incidence can be reduced by more than 50 percent.

Potassium nutrition has a strong influence on starch formation in tubers. In a comparative study it was found out that moderate SOP (K_2SO_4) doses increased starch content, whereas high MOP (KCl) supply resulted in a very low K content of starch in tubers.

Reducing sugars are known to be problematic during tuber processing because they induce undesired browning of chips and crisps. However, there is a strong negative correlation between K content and the amount of reducing sugars in tubers. Therefore an adequate K supply significantly decreases the content of reducing sugars in tubers. It also ensures a better coloration of potato chips. Field trials in Germany proved that SOP was more effective in preventing from enzymatic discoloration than did MOP.

K fertilization is also an important means to increase the frost resistance in cold growing regions. Tuber weight losses during storage was significantly reduced by sufficient K supply during the growing period.

The field experiments testing different K rates showed that most of the relevant potato quality and post harvest parameters were positively influenced by K. In most cases, SOP was the more efficient K source in comparison to MOP.